(12)特許協力条約に基づいて公開された国際出願

(19) 世界知的所有権機関
国際事務局

(43) 国際公開日
2005 年12 月29 日 (29.12.2005)

PCT

(10) 国際公開番号
WO 2005/124305 A1

(51) 国際特許分類⁷: G01L 5/16, 1/24

(21) 国際出願番号: PCT/JP2005/003650

(22) 国際出願日: 2005 年3 月3 日 (03.03.2005)

(25) 国際出願の言語: 日本語

(26) 国際公開の言語: 日本語

(30) 優先権データ:
特願2004-177786 2004 年6 月16 日 (16.06.2004) JP

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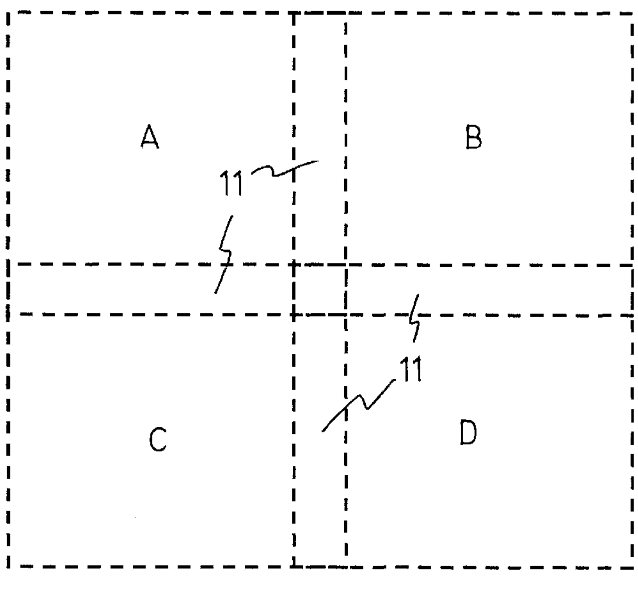
[続葉有]

(54) Title: OPTICAL TACTILE SENSOR

(54) 発明の名称: 光学式触覚センサ



(57) Abstract: An optical tactile sensor and an information integrating method capable of measuring large area force vector distribution. The integrating method of a marker image in an optical tactile sensor comprising a tactile section consisting of a transparent resilient body (1) and a plurality of markers (3, 4) provided therein, and a plurality of imaging devices (6, 6) for acquiring a marker image by photographing the behavior of the marker when an object (5) touches the tactile face (2) of the transparent resilient body (1), the method comprising a step for acquiring a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (1) using the plurality of imaging devices (6, 6) such that each imaging device (6) has an overlapped photograph region (11), and a step for integrating the partial images acquired by each imaging device (6) such that the identical markers in the overlapped photograph region match.

(57) 要約: 大面積力ベクトル分布計測を可能とする光学式触覚センサを提供する。大面積力ベクトル分布計測を可能とするための情報統合方法を提供する。透明弾性体１と該透明弾性体１内に設けた複数のマーカー３，４とから構成された触覚部と、該透明弾性体１の触覚面２に物体５

[続葉有]

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(81) 指定国 (表示のない限り、全ての種類の国内保護が可能): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) 指定国 (表示のない限り、全ての種類の広域保護が可能): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), ユーラシア (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), ヨーロッパ (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

添付公開書類:
— 国際調査報告書

２文字コード及び他の略語については、定期発行される各*PCT*ガゼットの巻頭に掲載されている「コードと略語のガイダンスノート」を参照。

が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する複数の撮像装置６，６とを有する光学式触覚センサにおけるマーカー画像の統合方法である。画像統合方法は、該複数の撮像装置の各撮像装置６によって、各撮像装置６が重複撮影領域１１を有するように該透明弾性体１の部分領域Ａ，Ｂ，Ｃ，Ｄを撮影して部分画像を取得するステップと、該重複撮影領域内の同一マーカーが一致するように各撮像装置６で取得された部分画像を統合するステップを有する。

明 細 書

光学式触覚センサ

技術分野

[0001] 本発明は、光学式触覚センサに係り、好ましくは、比較的大きな領域における力の加わり方を求めることに用いられる触覚センサに関するものである。

背景技術

[0002] 触覚センサによって接触面の接触状態を知ることを考える時、接触面の各点にかかる力は大きさと方向を持った3成分のベクトルである。これを図1の座標系でf(x,y)と表すことにする。ただしfはベクトルであるため、実際には各点においてx,y,z3成分を持つ。それぞれの成分を明示的に示す場合にはf(x,y)=[fx(x,y),fy(x,y),fz(x,y)]と表す。力分布が各接触点において3成分を持つことから、触覚センサによって接触面の力分布を再構成するためには少なくとも接触面の各点に対して3自由度以上の情報を得なければならない。

[0003] 本出願の発明者等は、3次元ベクトル分布の計測が可能な光学式触覚センサを提案している。かかる光学式触覚センサの原理について、図2に基づいて説明する。光学式触覚センサは、透明弾性体1とCCDカメラを用いて構成されている。透明弾性体内部に配置された球状マーカー3，4をCCDカメラで撮影することで、弾性体の表面に力が加わった時の弾性体内部の変形情報を計測し、力分布を再構築する。

[0004] 弾性体表面をxy平面、垂直方向をz軸にとりCCDカメラを用いてz方向から球状マーカーを撮影することにより、力が加わった際の測定点の移動をxy平面方向の移動ベクトルとして計測する。マーカーの変形情報から力ベクトル分布を再構築するため、弾性体内部の異なった深さに赤色球状マーカー、青色球状マーカーを測定点としてそれぞれN×N個配設することで深さの異なった2次元移動ベクトルを2つ求め、それぞれ異なった情報として扱うことで、情報量を増やして力ベクトル分布を求める。

[0005] このような光学式触覚センサの用途としては、当初、ヒューマノイド型ロボットにおけるロボットハンドへの適用等が考えられており、光学式触覚センサのアプリケーションとしては、小型の組み込み型センサを中心として研究されていた。しかしながら、このよ

うな光学式触覚センサは、3次元力ベクトル分布の計測が可能であると共に、センサ面が弾性体から構成されており、ロボットハンドのみならず、様々な分野におけるアプリケーションが期待される。

[0006] その一つとして、光学式触覚センサをいわゆる環境型触覚センサとして用いることが挙げられる。本明細書では、ロボットハンド等に組み込むことで用いられる組み込み型触覚センサに対して、環境に固定して使用するような触覚センサを環境型触覚センサと呼ぶ。しかしながら、環境に固定して使用する環境型触覚センサにおいては、例えば、椅子の座面、ベッド、床面等にセンサを適用することが想定されることから、大面積力分布計測が必要となると考えられ、ロボットハンド等への組み込みを前提としていた従来の小型の光触覚センサをそのまま適用することはできない。

特許文献1:国際公開公報WO02/18893 A1

発明の開示

発明が解決しようとする課題

[0007] 本発明の目的は、大面積力分布計測を可能とする光学式触覚センサを提供することにある。

[0008] 本発明の他の目的は、大面積力分布計測を可能とするためのマーカー情報取得方法及びマーカー画像統合方法を提供することにある。本発明のさらに他の目的は、大面積力分布計測を可能とする光学式触覚センサにおける力ベクトル再構築法を提供することにある。

課題を解決するための手段

[0009] 本発明は、かかる課題を解決するために創案されたものであって、透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面(接触面)に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する撮像手段とを有する光学式触覚センサにおいて、該撮像手段は複数の撮像装置から構成されていると共に、該複数の撮像装置の各撮像装置は、各撮像装置により取得される各撮影領域が部分的に重複する重複撮影領域を有するように設けてあり、該光学式触覚センサはさらに、該複数の撮像装置によって取得された各マーカー画像を統合する画像統合手段を有し、該画像統合手段は、該重複撮影領

域における同一マーカーを一致させるようにして各撮影領域を統合して統合画像を生成するように構成されていることを特徴としている。

[0010] 一つの好ましい態様では、該触覚部は複数の小面積触覚部を組み合わせることで構成された大面積触覚部である。尚、「大面積」、「小面積」という表現は相対的であるが、本明細書においては、「大面積」とは、ロボットハンドに組み込まれるような触覚部に比べて大きいことを意味し、「小面積」とは、「大面積」に比べて小さいことを意味する。「大面積」としては、椅子の座面、ベッド面、床面等が例示されるが、もちろん、これらよりも小さい面積のものも大面積に含まれる。

[0011] さらに好ましくは、触覚センサは、一つの小面積触覚部と該小面積触覚部に対応する一つの撮像手段からなるユニットを有し、該ユニットを複数組み合わせることで構成されている。触覚センサをセンサユニットから構成することで、任意の面積を有する触覚部を用意することができる。

[0012] 本発明が採用した他の技術手段は、透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する撮像手段とを有する光学式触覚センサを用いたマーカー画像の取得方法であって、該マーカー画像取得方法は、該撮像手段として複数の撮像装置を設け、該複数の撮像装置の各撮像装置によって、各撮像装置が重複撮影領域を有するように該透明弾性体の部分領域を撮影して部分マーカー画像を取得するステップと、該重複撮影領域内の同一マーカーが一致するように各撮像手段で取得された部分マーカー画像を統合して統合マーカー画像を生成するステップを有するものである。

[0013] 本発明が採用したさらに他の技術手段は、透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する複数の撮像装置とを有する光学式触覚センサにおけるマーカー画像の統合方法であって、該画像統合方法は、該複数の撮像装置の各撮像装置によって、各撮像装置が重複撮影領域を有するように該透明弾性体の部分領域を撮影して部分画像を取得するステップと、該重複撮影領域内の同一マーカーが一致するように各撮像装置で取得された部分

画像を統合するステップを有するものである。

[0014] 触覚部の構成としては、好ましくは、該触覚部は透明弾性体と該弾性体内に設けた複数のマーカー群とから構成されており、各マーカー群はそれぞれ多数の有色マーカーから構成されており、異なるマーカー群を構成するマーカーは群毎で互いに異なる色を有しており、該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを該撮像手段で撮影することを特徴とする。

[0015] また、本発明は、センシング用のマーカーを用いて各撮像手段のキャリブレーションを行うことを含むものである。本発明は複数の撮像装置を有するものであり、撮像手段のキャリブレーションが必要となるが、本発明は必須構成要素としてセンシング用のマーカーを有しており、該マーカーをキャリブレーション用のマーカーに兼用することができる。さらに、本発明には、このような光学式触覚センサを用いた力ベクトル再構成法も含まれる。力ベクトルの算出に寄与度の低いマーカーの振る舞いに関する情報を省いて力ベクトルを算出することで、力ベクトルの計算時間を短縮する。

発明の効果

[0016] 本発明は、複数の撮像手段を用いてマーカーを振る舞いに関する情報を取得するようにしたので、触覚部の面積が大きい場合であっても、良好に対応することができる。したがって、本発明に係るセンサを用いることで、大面積力ベクトル分布計測が可能であり、得られたマーカー情報から大きい面積を有する触覚面に加えられた力を求めることが可能となる。しかも、各撮像手段によって取得された画像情報の統合や各撮像手段のキャリブレーションに、センシング用のマーカーを利用することができ、より少ない構成要素でセンサを構成することができる。

発明を実施するための最良の形態

[0017] [A]光学式触覚センサの基本構成

[0018] 本発明に係る光学式触覚センサは、触覚部と撮像手段とを備えており、該触覚部は透明弾性体と該弾性体内に設けた複数のマーカー群とから構成されており、各マーカー群はそれぞれ多数の有色マーカーから構成されており、異なるマーカー群を構成するマーカーは群毎で互いに異なる色を有しており、該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを該撮像手段で撮影してマーカー画像を

取得し、該マーカー画像から得られるマーカーの振る舞いに関する情報を用いて該触覚面に加えられた力を求めるように構成されている。

[0019] 該有色マーカーの振る舞いを撮影することで、該弾性体に物体が接触した際における該有色マーカーの変位、ひずみ、傾きの少なくとも一つ以上を観測する。接触対象がセンサに接触した時の有色マーカーの情報から、透明弾性体内部のひずみ情報、さらにそこから計算された接触対象の形状や接触界面(弾性体の面、接触対象の面の双方を含む)に働く力の情報を検出するものである。本発明によれば、複数種類の情報を「色分け」というシンプルな方法によって個別に採集でき、光学式で複数種類の触覚情報を同時に得ることができる。そして、本発明によれば、「色分け」によって未知数の数以上の独立の観測値(マーカーの振る舞いに関する情報)を集め、逆問題を安定に解くことによって、力ベクトルを推定して再構築することができる。

[0020] 有色マーカーは撮像手段、一つの好ましい例ではCCDカメラ、によって撮影され、画像処理される。例えば、マーカーの振る舞いは、撮影されたマーカー画像から求められるマーカーの移動情報として取得され、物体接触時とそれ以前の状態(透明弾性体に外力が作用していない状態)の画像を比較し、マーカーの移動情報(例えば、移動ベクトル)を検出する。あるいは、常時(透明弾性体に外力が作用していない状態)では、マーカーが認識できないような配設態様でマーカーを透明弾性体に埋設しておき、透明弾性体に物体が接触した時に各マーカー存在位置周辺におけるひずみにより生じるマーカーの変位、変形、傾きに応じてマーカーが認識されるように構成し、有色マーカーの見え方等から情報を検出する。あるいは、他の好ましい態様では、マーカー(例えば、階段状の帯状マーカーの場合)の振る舞いは、マーカーの輝度の変化として取得される。

[0021] 光学式触覚センサには、該撮像手段で取得されたマーカーの振る舞いに関する情報(例えば、触覚面に物体が接触した時の各マーカーの移動情報である移動ベクトル)から触覚面に加えられた力ベクトルないし力ベクトル分布を再構成するための伝達関数が格納されている。伝達関数は、触覚面に加えられた力情報とマーカーの振る舞いに関する情報(例えば、移動ベクトル)とを関連付ける関数である。弾性体の触覚面に物体が接触した際の該有色マーカーを撮影してマーカー画像を取得し、該マ

ーカー画像から、マーカーの振る舞いに関する情報を取得し、取得した情報を伝達関数に入力することで、力ベクトルを出力として求める。伝達関数に入力されるマーカーの振る舞いに関する情報の数は、求めたい力ベクトルの数よりも多い。

[0022] 伝達関数は、弾性体の形状によっては、弾性体理論から導かれる式に基づいて算出することもできるが、弾性体の触覚面が自由曲面の場合には、伝達関数は、実測あるいはシミュレーションによって作成することが望ましい。実測あるいはシミュレーションによる伝達関数は、触覚面上に配置したサンプル点にx方向、y方向、z方向の所定の力が加えられた時のマーカーの振る舞いに関する情報(例えば、移動ベクトル)から求められる。

[0023] 図3は本発明に係る光学式触覚センサ装置の原理図であり、センサ装置は、透光性弾性部材からなる透明弾性体1を備えており、透明弾性体1は曲面状の触覚面(センサ面)2を有している。透明弾性体1には、触覚面2に近接して、触覚面2の曲面に沿うようにして多数の有色マーカー3，4が埋設されており、透明弾性体1と有色マーカーとで触覚部を構成している。

[0024] 有色マーカーは、2つの有色マーカー群から構成されており、2つのマーカー群は触覚面2から異なる深さに夫々埋設されている。一方のマーカー群を構成する有色マーカー3と、他方のマーカー群を構成する有色マーカー4とは互いに異なる色(例えば、一方が赤で、他方が青)を有している。

[0025] 透明弾性体1の触覚面2に物体5が接触すると、透明弾性体1の内部に設けられた有色マーカー3，4が変位あるいは歪みを起こすように構成されている。センサ装置はさらに、撮像手段としてのカメラ6、及び光源7を備えている。光学式カメラ6は、透明弾性体1を挟むようにして、物体5が接触する側とは反対側(触覚面2から離隔した側)に位置させて配設されており、マーカー3，4の変位、歪みをカメラ6で撮影するようになっている。光源7は、導波管(光ファイバ)を用いて導くものであってもよい。撮像手段であるカメラ6によって取得されたマーカー3，4の画像情報がコンピュータ8に送信されてマーカー画像がコンピュータ8の表示部に表示され、マーカー画像からマーカーの振る舞い(変位、歪、傾き)に関するマーカー情報(例えば、移動情報の一つである移動ベクトル)がコンピュータ8の演算部によって計測される。コンピュータ8の記

憶部には前述の伝達関数が格納されており、演算部によって、該伝達関数及び該マーカー情報(例えば、移動情報)を用いて、物体5から触覚面2に作用した力分布を再構築する。

[0026] 透明弾性体1は好ましくはシリコンゴムから形成されるが、他のゴム類やエラストマー等の他の弾性部材から形成されてもよい。マーカーは、好ましくは、弾性部材から形成され、さらに好ましくは、透明弾性体1と同じ材料から構成され、一つの好ましい態様では、シリコンゴムに色素を加えたものから構成される。マーカーによって弾性体本体の変形が阻害されてはならないので、マーカーも弾性部材(好ましくは、弾性体と同等の弾性定数を有するもの)から形成されていることが好ましい。また、マーカーは、弾性体本体の変形を阻害しない程度に十分に微小なものであれば、マーカーの材質は特に限定されない。また、弾性体の部分がマーカーを構成するものであってもよい。

[0027] 本発明では、透明弾性体1の中に光学的なマーカーを多数分布させ、弾性体1に物体が接触することによる弾性体1の変形によって、該マーカーに変位、ひずみ、傾きが生じる状況をカメラで撮影することにより、接触対象の情報や接触によって引き起こされた弾性体内部の変位、ひずみの情報を検出する。図3では2つのマーカー群を示したが、マーカー群の数は限定されず、たとえば、触覚面2に沿って3層状に三つのマーカー群を配設してものでもよい。

[0028] 撮影手段としてのカメラは、ディジタル式カメラ、すなわち画像データを電気信号として出力するカメラであり、一つの好ましい例では、CCDカメラである。本発明に係る撮像手段はCCDカメラに限定されるものではなく、例えばC-MOS式イメージセンサを用いたディジタルカメラでもよい。マーカーとしてRed, Green, Blueの3種類用意したとき、これらを個別に捉えるためには、(1)撮像素子のカラーフィルタで分ける(この場合カメラのRGB出力を見ればそのまま各マーカーを個別に撮影したことになる)という方法と、(2)撮像素子は光の強度のみ捉え、光源としてRed, Green, Blueを用意する(Redを光らせたときにはRedのマーカーからのみ反射光が有り、他の二種類のマーカーは光を吸収するため，結果的にカメラはRedのマーカーのみ捉える。これを時分割でGreen, Blueに対しても行えば(1)と等価な情報が得られる。)という方法の二つが有

る。

[0029] [B]環境型触覚センサの構成

[0030] 本発明に係る環境型触覚センサの実施例を説明する。環境型触覚センサは、複数のセンサユニットから構成されている。図4左図に示すように、センサユニットは、一つの小面積触覚部10と小面積触覚部10を撮影する撮像手段である一つのCCDカメラ6とから構成されている。小面積触覚部10は、前述の基本構成で説明したように、透明弾性体と透明弾性体内部に設けた有色マーカーとから構成され、透明弾性体の触覚面に物体が接触すると、透明弾性体の内部に設けられた有色マーカーが移動し、有色マーカーの移動をCCDカメラ6で撮像するようになっている。そして、図4右図に示すように、複数のセンサユニットを組み合わせることでセンサ面の大面積化を図るものである。小面積触覚部10を、互いに同一面を形成するように、触覚部の端縁同士を当接させて敷き詰めることで大面積触覚部100を形成する。図示ものでは、小面積触覚部10は平面視方形状の形状を有している。小面積触覚部の形状は方形に限定されないが、複数の小面積触覚部を敷き詰める際には、方形状の触覚部が有利である。また、図示ものでは、平面状の触覚面10を備えた小面積触覚部を示したが、触覚面10は平面に限定されず、自由曲面からなる触覚面でもよい。

[0031] 複数のCCDカメラ6を用いることで、それぞれのカメラによって取得された画像情報を統合する必要がある。図5は、複数台のカメラ画像の統合について説明する図である。このような画像は、例えば、コンピュータ8の表示部に表示される。先ず、複数台のカメラ6によって、各撮影領域が互いに部分的に重複するように小面積触覚部10の画像をそれぞれ取得する。次いで、重複撮影領域11中のマーカーが互いに一致するように各カメラ画像を合成することで画像情報の統合を行う。図5において、黒丸は青色マーカー、白丸は赤色マーカーであって、カメラ1の撮影領域とカメラ2の撮影領域は重複撮影領域11を有している。カメラ1の撮影領域において重複撮影領域11に対応する領域に含まれる青色マーカー及び赤色マーカーと、カメラ2の撮影領域において重複撮影領域11に対応する領域に含まれる青色マーカー及び赤色マーカーとを一致させるようにして、カメラ1によって撮影された部分画像とカメラ2によって撮影された部分画像とを合成する。ここでは、球状のマーカーに基づいて説明したが

、後述する他の形状のマーカーを用いても同様に画像を統合することができる。

[0032] 図4に示す4台のCCDカメラで撮像した画像を図6に示す。各CCDカメラで取得した撮影領域をそれぞれA，B，C，Dとすると、領域Aと領域B、領域Aと領域C、領域Bと領域D、領域Cと領域Dのそれぞれにおいて重複撮影領域11が形成されるように各撮影領域A，B，C，Dを統合する。尚、図6ではマーカーは省略してある。各カメラは、カメラ毎に予め決められた領域におけるマーカーの振る舞いを撮影するように構成されており、該決められた領域は、互いに重複する領域を有している。一つの態様では、各カメラは、それぞれ透明弾性体の所定の部分領域を撮像するように予め設定されており、各カメラによって取得される各所定の部分領域の画像を統合することで、透明弾性体全体の画像を取得できるように構成される。

[0033] 複数台の撮像手段（CCDカメラ）を用いる場合のカメラのキャリブレーションについて説明する。カメラキャリブレーションは一般に得られた画像に生じているレンズによる歪の補正と世界座標系におけるカメラの位置と向きを求めるために行う。レンズの歪は広角なレンズを用いた際には必ず発生するものであり、カメラの位置・向きは画像情報を用いて決定することが最も正確である。本触覚センサにおいては画像情報と実際の位置との関係を求めることは必要なことであり、カメラキャリブレーションを行う必要がある。通常、複数台のカメラを用いた計測系では次のような手順を踏む必要がある。まず世界座標系に対して既知の位置に間隔の分かっている縞模様や白黒のタイル状模様を配置し、それを撮影する。次に，その撮影画像を用いてレンズ歪がない場合に撮影されるはずの画像とのズレを計算し，レンズ歪とカメラの位置・向きを求める。ここで、同じように複数台のカメラを用いる環境型触覚センサにおいては、前述の「既知の位置に間隔の分かっている縞模様や白黒のタイル状模様」は、既にセンシング用の有色マーカーとして配置され、画像として取得可能な状態となっている。そのため，本来計測系を組む前に行わなければならないカメラキャリブレーションを計測系を組んだ後にいつでも行うことが可能となる。

[0034] ［C］触覚面に加えられた力ベクトル分布の再構成法

[0035] 光学式触覚センサによって得られたマーカーの振る舞いに関する情報（例えば、マーカーの移動情報の一つである移動ベクトル）から触覚面に加えられた力ベクトル分

布を求めるには、マーカーの振る舞いに関する情報(例えば、移動情報)Mから力情報Fへの変換が必要となる。マーカー情報Mから力情報Fへの変換は、式F=HMによって行なわれる。以下に、マーカー情報から力ベクトル分布を再構成する手法について、図7，8を参照しながら、マーカーの移動ベクトルから力ベクトル分布を求める手法に基づいて説明する。図7と図8とは、図7が平面状の触覚面、図8が自由曲面状の触覚面を示している点を除き、実質的に同じ内容である。ここでは簡単のため二次元断面(図のy軸方向は考えない)について考えるが、一般的な三次元の場合でもアルゴリズムは同一である。

[0036] fは接触表面にかかる力ベクトル、m,nはそれぞれBlue，Redの色付けをしたマーカーのCCD素子上での移動ベクトルを表す。適当な離散化によって有限な点数(図7，図8では4点)について考える。前述のように力ベクトルはそれぞれ3成分(x,y,z成分)をもつが、ここでは2成分(x,z成分)を考える。ここでは、説明の便宜上、図のようにx方向成分のみ観測されたとする。

[0037] f=[fx(1),fx(2),fx(3),fx(4),fz(1),fz(2),fz(3),fz(4)]の8成分が求めたい力分布であり、

m=[m(1),m(2),m(3),m(4)],

n=[n(1),n(2),n(3),n(4)]が観測される移動ベクトルである。このm,nをまとめてxと書くことにする。

すなわち、x=[m(1),m(2),m(3),m(4),n(1),n(2),n(3),n(4)]となる。

ここで、点1においてx方向単位力(大きさ1の力)が加えられたときに観察される各マーカーの移動ベクトルm,nをまとめてMx(1)と書く。

すなわち、

Mx(1)=[m(1),m(2),m(3),m(4),n(1),n(2),n(3),n(4)]

when f=[1,0,0,0,0,0,0,0]

[0038] 同様に、点1においてz向単位力が加えられたときに観察される各マーカーの移動ベクトルをMz(1)、点2おいてx方向単位力が加えられたときに観察される各マーカーの移動ベクトルをMx(2)等、以下同様に定める。線形弾性体(加えられた力分布と変位の間に線形加算関係が成り立つ弾性体。多くの弾性体はこの性質を満たす)の場合、一般的な力f=[fx(1),fx(2),fx(3),fx(4),fz(1),fz(2),fz(3),fz(4)]が与えられたときに生じる

移動ベクトルxは次のように書かれる。

X=Mx(1)*fx(1)+Mz(1)*fz(1)+Mx(2)*fx(2)+…+Mz(4)*fz(4)

[0039] これを行列形式で書くと、X=H*fとなる。ただしH=[Mx(1);Mx(2);…;Mz(4)]。このHを、力fから変位xに伝達させるための写像と言う意味で伝達関数と呼ぶ。

要素ごとに書くと次のようになる。

[数1]

$$\begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix} = \begin{bmatrix} Hmx(1,1) & Hmz(1,1) & Hmx(1,2) & Hmz(1,2) & Hmx(1,3) & Hmz(1,3) & Hmx(1,4) & Hmz(1,4) \\ Hmx(2,1) & Hmz(2,1) & Hmx(2,2) & Hmz(2,2) & Hmx(2,3) & Hmz(2,3) & Hmx(2,4) & Hmz(2,4) \\ Hmx(3,1) & Hmz(3,1) & Hmx(3,2) & Hmz(3,2) & Hmx(3,3) & Hmz(3,3) & Hmx(3,4) & Hmz(3,4) \\ Hmx(4,1) & Hmz(4,1) & Hmx(4,2) & Hmz(4,2) & Hmx(4,3) & Hmz(4,3) & Hmx(4,4) & Hmz(4,4) \\ Hnx(1,1) & Hnz(1,1) & Hnx(1,2) & Hnz(1,2) & Hnx(1,3) & Hnz(1,3) & Hnx(1,4) & Hnz(1,4) \\ Hnx(2,1) & Hnz(2,1) & Hnx(2,2) & Hnz(2,2) & Hnx(2,3) & Hnz(2,3) & Hnx(2,4) & Hnz(2,4) \\ Hnx(3,1) & Hnz(3,1) & Hnx(3,2) & Hnz(3,2) & Hnx(3,3) & Hnz(3,3) & Hnx(3,4) & Hnz(3,4) \\ Hnx(4,1) & Hnz(4,1) & Hnx(4,2) & Hnz(4,2) & Hnx(4,3) & Hnz(4,3) & Hnx(4,4) & Hnz(4,4) \end{bmatrix} \begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix}$$

ただしHmx(x1,x2)は，座標x=x2の表面に加わったx方向単位力による座標x=x1における、mマーカーがある深さでのx方向変位量を表す。同様に、Hnz(x1,x2)は座標x=x2の表面に加わったz方向単位力による座標x=x1における，nマーカーがある深さでのx方向変位量を表す。

[0040] 観測されたxからfを求めるにはHの逆行列をかけてやればよい。すなわちf=inv(H)*x（式1）である。ただしinvは逆行列（一般には一般化逆行列）を表す。

要素ごとに書くと数2のようになる。

[数2]

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

ただしImx(1,1)等はinv(H)の各要素であるが，結局のところfx(1)を計算するためのm(1)の寄与を表す。

[0041] 伝達関数によって定まった行列の逆行列を使うことで未知数を定める場合、未知数の個数を観測されたデータの個数が上回っているか同数である必要がある。この問題を解決するために色分けした2層のマーカー群を用意し、2層のマーカー群の各マーカーの移動を取ることによって独立な観測データ数を8つまで増やしている。

[0042] 一般的な三次元の場合(この図ではy軸が追加された場合)、一点における力ベクトルは3自由度、マーカーの水平移動ベクトルは2自由度である。もしサンプリング点が同様に4点であったとすると、未知数は

f=[fx(1),fy(1),fz(1),fx(2),fy(2),fz(2),fx(3),fy(3),fz(3),fx(4),fy(4),fz(4)]の12個存在するのに対して、観測される値は移動ベクトル

m=[mx(1),my(1),mx(2),my(2),mx(3),my(3),mx(4),my(4)]の8個であり、やはり足りない。これを2層に分けて観測することにより16個の観測データを得ることが出来、これにより12個の未知数を同定することになる。以上のようなアルゴリズムを用いて、CCD画像から力ベクトルを推定する。他のマーカーを用いた他の測定方式でも、観測されるデータが異なるだけで、色分けという工夫によって未知数の数より多い独立な観測値(マーカーの振る舞いに関する情報)を集め、逆問題を安定に解くことによって力ベクトルを推定する点では同じである。

[0043] [D]力ベクトル分布の再構成に用いる伝達関数

[0044] 次に、伝達関数(行列H)を求めるための手法を説明する。ある特徴的な形の弾性体(例えば半無限弾性体)においては、表面に加わる力と内部変位の関数として、前述の微小領域で満たすべき関係式を弾性体内部のあらゆる場所で満たすことが出来る関数が数式の形で発見されている。このような形の場合には、この関数にメッシュ状に区切った弾性体表面(触覚面)の座標と内部マーカーの座標を代入すれば行列Hが求まる。

[0045] ここで数式の形で発見されているとは、表面応力をf(x1)、内部変位をm(x2,y2)とした場合に、m(x2,y2) = G(f(x1),x2,y2)という形で内部変位を表面応力から求める関数Gが発見されているということである。このとき例えば図7、図8で点1に力が加わったときのマーカー2における変位はm(2,y2) = G(f(1), 2,y2)によってもとまる。ただしy2はマーカーの深さ(既知)である。

[0046] 弾性体形状によっては、弾性体形状を半無限大弾性体と仮定することによって上述のような数式を用いてH行列を取得できる。しかし、例えば半球のような自由曲面に対して同様に半無限大弾性体の式を当てはめることは困難である。したがって、何らかの別手段で表面応力と内部変位を関連付ける必要がある。

[0047] そのために提案する第一の手法は、数値シミュレーションによって表面応力と内部変位を関連付ける手法である。提案するセンサで適用するに際しては、まず表面をメッシュに区切り、各メッシュに単位応力(x方向、y方向、z方向)が加わった際のマーカーの移動量をシミュレーションで計算する。

[0048] 第二の手法は実際に力を加えることである。自由曲面を有する弾性体の触覚面に、既知の力F1,F2,F3,F4…Fnを加える。加えられたそれぞれの力に対するマーカーの移動ベクトルM1,M2,M3,M4,..Mnを計測し、これを保存する。F1は、F1x、F1y、F1zの3つのベクトルであり、これらの力を加えたときに夫々対応するマーカーの移動ベクトルはM1x,M1y,M1zとなる。既知の力と得られた情報(移動ベクトル)を用いて行列Hを作成する。以下具体的に説明する。

[0049] 弾性体表面(触覚面)上に多数のサンプル点を離散的に配置する。好ましくは、サンプル点は触覚面の全域をカバーするように配置される。一つの態様では、触覚面上の離散的な多数のサンプル点の配設は、極座標を用いて配設される(平面視同心状に配設される)。他の態様では、サンプル点は平面視格子状に配設される。

[0050] 各サンプル点において、x方向、y方向、z方向にそれぞれ作用する既知の大きさの力と、かかる力が作用したそれぞれの場合のマーカーの移動ベクトルとを関連付ける情報を取得する。一つの好ましい方法では、各サンプル点にx方向、y方向、z方向の所定の力をそれぞれ加え、その時のマーカーの移動ベクトルをそれぞれ計測して、保存する。サンプル点に加える力ベクトルのx方向、y方向、z方向の取り方は、力ベクトルを用いて、触覚面に加えられる任意の力を表示できるものであれば、その方向は限定されない。

[0051] 各サンプル点に加える力は既知の力であり、一つの好ましい態様では、一定の大きさの力、例えば100[gf]をそれぞれx方向、y方向、z方向からサンプル点に加えて、それぞれの場合のマーカーの移動ベクトルを計測する。また、各サンプル点に加える

力は既知の力であれば、必ずしも同じ大きさの力でなくてもよく、異なる既知の力に基づいてマーカーの移動ベクトルを計測した場合には、後で、マーカーの移動ベクトルの大きさを正規化すればよい。

[0052] このようにして、弾性体理論に基づく数式、シミュレーションあるいは実測によって、力情報Fとマーカーの振る舞いに関する情報（例えば、移動情報）Mとを結び付ける伝達関数である行列Hを作成する。光学式触覚センサ装置は記憶手段、演算処理手段を有しており、予め作成された行列Hは記憶手段に格納されている。透明弾性体の触覚面に物体が当接して、触覚面に任意の力が作用した場合に、撮像手段によってマーカー画像を取得する。取得したマーカー画像から演算処理手段によって、マーカー移動ベクトルを計測する。計測されたマーカー移動ベクトルを行列Hに入力して演算処理手段で計算することで、弾性体の触覚面に作用した力ベクトル分布が出力される。

[0053] [E]計算時間短縮法

[0054] ここで、行列Hの要素数が大きくなると移動情報から力分布を計算する時間が長くなってしまう。これはある点に加えられた力を求める際に、全てのマーカーの移動情報を用いることに起因する。実際に前述のアルゴリズムを適用する場合、H行列が巨大になり、（式1）の行列演算に時間がかかる。一例を挙げればメッシュが100x100であった場合、観測点が10,000点あるためにH行列は10,000
x 10,000という巨大な行列となる。一般にセンサ面をNxNに区切った場合、観測点がNの2乗個あるためにH行列のサイズはNの二乗×Nの二乗となる。すると（式1）の行列演算にはNの4乗の時間がかかることになる。このことは、本発明に係る環境型触覚センサ（大面積触覚部を有する場合が多いと考えられる）においては顕著に表れる。したがって、計算時間を短縮するための手法が必要となる。

[0055] 提案する手法はH行列の一部を切り出して用いるというものである。上述のように、H行列には全ての格子点に加わる力と全てのマーカーの移動との対応関係が記述されている。しかし現実問題として、例えば力の加わる点とマーカーとの距離が充分離れていれば影響を無視することが出来る。すると例えば図7、図8では、f(1)を計算するには1ー2番目のマーカーのみ、f(2)を計算するには1ー3番目のマーカーのみの移

動量を使えばよいと仮定することによって行列のサイズを小さくすることが出来る。この例における新しい行列は以次のようになる。

[0056] 元の(式1)f=inv(H)*xは数3のとおりであった。

[数3]

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

[0057] この式が、距離の離れたところの寄与を無視することにより数4のようになる。

[数4]

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

0と置いたところが無視すべき距離の離れた点である。この部分は計算する必要が無いため、より高速に計算することが出来る。この高速化は前述のように格子サイズNが大きくなるほど加速度的に効果が現れる。

[0058] これは、力ベクトルを求めたい場所を含むある面積を切り出して使うのと等価である(図10)。図のものでは、触覚面全体の2次元画像において、力ベクトル分布を求めたい場所の近傍領域を設定している。ここで、力ベクトルを求めたい場所の近傍領域を設定する場合に、必ずしも、近傍領域は2次元画像における距離のみに基づいて判断されるものではない。すなわち、力の加わる点とマーカーとの距離は空間距離であって、マーカー群が弾性体内に積層されているような場合には、マーカーが設けられた深さを考慮した方が望ましい場合もある。

[0059] 触覚面が自由曲面の場合、一概に距離の離れた場所の寄与が小さいとも言い切れない。そこで、計算時間を短縮する他の方法を提案する。まず、実測あるいはシミュレーションによって伝達関数(逆行列)を求める。このような伝達関数の作成法は、既に述べた。例えば、実測に基づく伝達関数の行列の要素を見た時に、行列のある要素が0に近ければ、かかる要素と積算されるマーカーは、ある力ベクトルを求めるのに無視してもよいマーカーであると考えられる。伝達関数で行列のある要素が0に近い部分を自動的に計算から省いて、力ベクトルを計算することができる。例えば、力ベクトルの再構成において無視できる程度の指標を示す閾値を行列要素に対して設定し、該閾値よりも小さい値を有する行列要素の値を0とする。

[0060] さらに、計算短縮化方法の改良について説明する。画像のある領域を切り出すという点に関しては、前述の計算時間短縮法と同じである。前述の方法では切り出し領域がありその内部の情報についてのみ扱っていたのに対して、改良手法は切り出し領域外にも計算する力のサンプリング点を用意する。マーカーの移動に関してはあくまで切り出し領域内の情報のみを扱う。これは領域外からの力の影響を考慮してやるためのサンプリング点となる。すなわち、切り出し領域内におけるマーカーの移動は、切り出し領域外に加わる力の影響をある程度受けていると考えられるため、切り出し領域内におけるマーカーの移動情報に基づく力ベクトルの再構成時において、切り出し領域内に作用したであろう力のみならず、切り出し領域外に作用したであろう力をも算出することで、切り出し領域外に作用した力を考慮しつつ、切り出し領域内に作用した力を再構築するものである。

[0061] さらに、領域外の力のサンプリング点は切り出し領域から離れるに従い、まばらになっていくように設定する。これは領域から離れれば離れるほど影響は軽微になるため少数のサンプリング点で代表させてもよいと考えたためである。図11に基づいて説明すると、5×5点のサンプリング点に対応する小領域を触覚部の画像において設定する。小領域内にサンプリング点を密に配設する。小領域外にも力のサンプリング点を配置する。小領域外の力のサンプリング点は、小領域から離隔するに従って疎に配置される。図示のものでは、小領域に隣接する部位においては、小領域内と同じ密度でサンプリング点を密に配置し、該小領域から離れるに従い、サンプリング点を疎に

配置するようになっている。

[0062] そして、小領域内におけるマーカーの移動情報を用いて、小領域内外に配置したサンプリング点における力ベクトルを計算する。計算された力ベクトルのうち、小領域内にある力ベクトルの少なくとも一部の結果のみを最終的な計算結果として採用し、保存する。図11のものでは、5×5の小領域における3×3の力のサンプリング点における力ベクトルを最終的な計算結果として保存する。小領域外におけるサンプリング点及び小領域内における採用されなかったサンプリング点の力ベクトルは捨てる。そして、切り出した小領域を順次ずらして、力ベクトルを取得することで、センサの計測領域全体における力ベクトル分布を取得する。図11では、小領域の一部のサンプリング点における力ベクトルを採用しているが、小領域内の全てのサンプリング点における力ベクトルを採用してもよい。また、図11では、小領域の一部の複数のサンプリング点における力ベクトルを採用しているが、小領域内の一つのサンプリング点における力ベクトルのみを採用してもよい。図11では、5×5点の小領域を示したが、切り出す小領域の大きさは限定されない。この改良手法によると、前述の計算時間短縮法に比べて、計算量は増加してしまう結果になるが、高速化手法適用前に比べると十分な計算時間短縮がある。

[0063] 改良された手法について、図12乃至図15に基づいて説明する。図12では、改良手法の説明の便宜上、図7、図8に示すものに比べてマーカー点数を増やしてある。マーカー点数を増やしたことにより、対応する数式中の要素数が増加してしまうため、図13において、ある一点の力に対するマーカーnのx、z方向移動についてのみ表記する。数式3における行列inv(H)の要素Imx(1,1),Imx(2,1),Imx(3,1),Imx(4,1),Imz(1,2),Imz(2,2),Imz(3,2),Imz(4,2)に対応する部分のみを取り出し、マーカー点数を増加させることと等価である。

[0064] 改良前の高速化手法は求めようとしている力の加わっている点の近傍に存在するマーカーの移動情報のみを用いることであり、図14に示すように、m_{10}ーm_{14}のマーカーの移動情報のみを用いるものである。これに対し、改良後の高速化手法を図で表現すると、図15のようになる。すなわち、力のサンプリング点として、F8のみならず、F_2, F_5, F_9, F_{11}, F_{14}を配置する。そして、計算された力ベクトルにおいて、F_{x8}、F_{z8}に

おける力ベクトルのみを採用する。

[0065] [F]マーカー群の他の実施例

[0066] 光学式触覚センサの触覚部は、好ましい態様では、該透明弾性体には、複数のマーカー群が埋設されており、各マーカー群はそれぞれ多数のマーカーから構成されており、異なるマーカー群を構成するマーカーは群毎で互いに異なる色を有しており、さらに、該マーカー群は互いに異なる空間的配列を有している。この異なる空間的配列の例としては、該弾性体の肉厚内で積層状に配設された複数のマーカー群が挙げられる。積層状のマーカー群の具体例では、該マーカー群を構成するマーカーは球状の微細小片であり、各層のマーカー群を構成する球状マーカーは互いに異なる色を有する。他の空間的配列の例では、互いに交差するように配設された複数のマーカー群が挙げられる。さらに他の空間的配列としては、各マーカー群は同じ方向に延出する複数の面の群から構成されており、該面の延出方向および色は、各マーカー群毎で互いに異なるものが挙げられる。有色マーカーの形状は特には限定されないが、好適な例を挙げると球状、円筒状、円柱状、帯片状、平面状の形状が考えられる。

[0067] 本発明について、一つの好ましい態様である球状マーカーに基づいて説明したが、本発明に用いられるマーカーの形状や配設構成は前述のものに限定されない。他のマーカーの形状および配設構成について図16乃至図19に基づいて説明する。これらのマーカーの詳細については、国際公開公報WO02/18893 A1の記載を参照することができる。また、マーカーの形状や配設態様は、図示のものあるいは前記国際公開公報に記載されたものに限定されるものではない。

[0068] 図16には、微小断面を有する極細円筒体あるいは極細円柱体からなる色マーカーが示してある。透明弾性体1の厚さ内には、触覚面2から異なる深さにおいて、多数の青色マーカー30を垂直状に配設して構成した青色マーカー群と、多数の赤色マーカー40を垂直状に配設して構成した赤色マーカー群がそれぞれ触覚面2に沿って触覚面2から異なる深さに積層状に配設されている。マーカーは、弾性体に接触する物体とカメラとを結ぶ仮想線に沿って延出している。各マーカーの配設態様は図示のものに限定されず、また、互いに異なる色を有する3つ以上のマーカー群を設け

てもよい。

[0069] 図17上図には、弾性体1内に階段状に配設された傾斜面状の面マーカー300，400が示してある。好ましくは、弾性体1の部分（階段状の界面）がマーカー300，400を形成するが、別体の面マーカーを弾性体1内に埋設してもよい。階段状の界面は2つの同じ方向を持った面群に分けることが出来る。それぞれの群を同一色に着色しておく（一方の界面300が青、他方の界面400が赤）。ある点における2色の輝度の観測によってその点における力ベクトルの水平、垂直成分を情報として含んだ観測値が得られる。これらをセンシングすることによって力ベクトルの面分布を再構成することが出来る。図17上図には、2色の帯状の面マーカーを図示したが、3色を有する面マーカーを用いてもよい。図17下図のように底面に微細な立方体の集まったいわゆるピラミッド構造を用い、同一方向を向いた3組の面群をそれぞれ同一色に着色すれば（例えばRed，Green，Blue）、3色輝度の比率で接触面水平にかかる力の自由度を、3色の合計輝度によって面垂直にかかる力をそれぞれ求めることが出来る。

[0070] 図18には、弾性体内で、複数の並設された赤色薄肉帯片からなるマーカー群、複数の並設された青色薄肉帯片からなるマーカー群の2つのマーカー群を、それぞれのマーカーが互いに交差（図示のものでは直交）するように配設したものを示している。複数のマーカー群の空間的配設関係はこれに限定されない。また、マーカーを構成する帯片の表裏を異なる色から形成してもよい。図では、帯片マーカーの面部は、観測方向に沿って延出しているが、該帯片マーカーの面部は、観測方向に対して傾斜状に延出するものでもよい。

[0071] 図19は、複数の平面マーカーを有する触覚部を示している。平面マーカーは常時は隠蔽マーカーによって隠蔽されている。平面マーカーは複数の部位に区画されており、各区画には互いに異なる色が付してあり、各平面マーカーにおける同色を有する区画がマーカー群を構成している。該平面マーカーと該隠蔽マーカーとは、互いに間隔を存して該透明弾性体に設けてあり、該透明弾性体に力が作用しない状態においては該平面マーカーが隠蔽されて観測されない。剪断歪みが生じると、隠蔽マーカーと有色マーカーの位置がずれて、色づくように構成されている。図示のものでは、円形マーカーは、円の中心から三等分されて三つの扇状部に分割されており、

それぞれ赤、緑、青に塗り分けられており、発生した色からひずみの方向を知ることが出来る。

産業上の利用可能性

[0072] 本発明は触覚センサに広く適用することができ、好適な例としては、椅子の座面にセンサを用いることによる座っている人間の臀部に加わる圧力分布の計測、ベッドにセンサを用いることによる寝ている人間の圧力分布計測、床面にセンサを用いることによる歩行計測や重心動揺計測等に用いられる。

図面の簡単な説明

[0073] [図1]触覚センサと接触対象の間に生じる力ベクトル分布を示す図である。

[図2]光学式触覚センサの原理図である。上図は透明弾性体の平面図（CCD画像）であり、下図は透明弾性体の側面図である。透明弾性体には、2種類のマーカー群が埋設されている。透明弾性体に下方から力が作用すると、マーカーは左図から右図のように移動する。

[図3]本発明に係る光学式触覚センサの模式図である。

[図4]センサ面の大面積化を説明する概略図である。左図はCCDカメラ1台と弾性体部で構成された1ユニットを示す。右図は1ユニットを敷き詰めることで大面積化を行ったものを示す。

[図5]複数の撮像手段によって取得された画像情報を統合方法を示す図である。

[図6]図4に示すセンサによって取得される画像情報の概略図である。

[図7]接触表面（平面）にかかる力ベクトルとマーカーの移動を説明する図である。

[図8]接触表面（自由曲面）にかかる力ベクトルとマーカーの移動を説明する図である。

[図9]力ベクトル分布の再構成に用いる伝達関数の作成法の説明図である。

[図10]統合された複数台カメラによって撮影された画像であり、力ベクトル再構築の計算時間の短縮法の説明図である。ある点に加わる力を求める際、その近傍領域にあるマーカーの移動情報のみを用いて力を計算する。

[図11]計算短縮法における改良手法の概念図である。図中、黒丸及び白丸は力のサンプリング点を表し、黒丸は計算後利用する計算結果を表す。

[図12]マーカー点数を増加させたものを示す図である。

[図13]マーカー点数を増加させたものを示す図であり、ある一点の力に対するマーカーの移動に注目した図である。

[図14]図13に基づいて、図10に示す高速化手法を説明する図である。

[図15]図13に基づいて、改良手法を説明する図である。

[図16]マーカーの他の実施例(円柱状マーカー)を示す図である。

[図17]マーカーの他の実施例を示す図であり、上図は、階段状の帯状マーカー、下図は、ピラミッド形状のマーカーを示している。

[図18]マーカーの他の実施例(交差状の帯片マーカー)を示す図である。

[図19]マーカーの他の実施例(色分けされた平面マーカー)を示す図である。

符号の説明

[0074] 1 透明弾性体

2 触覚面(接触面)

3 マーカー

4 マーカー

5 物体

6 撮像手段

7 光源

8 コンピュータ

10 小面積触覚部

100 大面積触覚部

11 重複撮影領域

請求の範囲

[1] 透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する撮像手段とを有する光学式触覚センサにおいて、

該撮像手段は複数の撮像装置から構成されると共に、該複数の撮像装置の各撮像装置は、各撮像装置により取得される各撮影領域が部分的に重複する重複撮影領域を有するように設けてあり、

該光学式触覚センサはさらに、

該複数の撮像装置によって取得された各マーカー画像を統合する画像統合手段を有し、

該画像統合手段は、該重複撮影領域における同一マーカーを一致させるようにして各撮影領域を統合して統合画像を生成するように構成されていること、

を特徴とする光学式触覚センサ。

[2] 請求項1において、該光学式触覚センサは、各撮像装置によって取得された画像を表示する画像表示部を含むことを特徴とする光学式触覚センサ。

[3] 請求項1，2いずれかにおいて、該触覚部は複数の小面積触覚部を組み合わせることで構成された大面積触覚部であることを特徴とする光学式触覚センサ。

[4] 請求項3において、触覚センサは、一つの小面積触覚部と該小面積触覚部に対応する一つの撮像手段からなるユニットを有し、該ユニットを複数組み合わせることで構成されていることを特徴とする光学式触覚センサ。

[5] 請求項1乃至4いずれかにおいて、該触覚部は透明弾性体と該弾性体内に設けた複数のマーカー群とから構成されており、各マーカー群はそれぞれ多数の有色マーカーから構成されており、異なるマーカー群を構成するマーカーは群毎で互いに異なる色を有しており、該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを該撮像手段で撮影することを特徴とする光学式光触覚センサ。

[6] 透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する撮像手段とを有する光学式触覚センサを用いたマーカー画

像の取得方法であって、

該マーカー画像取得方法は、

該撮像手段として複数の撮像装置を設け、該複数の撮像装置の各撮像装置によって、各撮像装置が重複撮影領域を有するように該透明弾性体の部分領域を撮影して部分マーカー画像を取得するステップと、

該重複撮影領域内の同一マーカーが一致するように各撮像手段で取得された部分マーカー画像を統合して統合マーカー画像を生成するステップ、

を有する光学式触覚センサを用いたマーカー情報取得方法。

[7] 請求項6に記載の方法において、該触覚部は透明弾性体と該弾性体内に設けた複数のマーカー群とから構成されており、各マーカー群はそれぞれ多数の有色マーカーから構成されており、異なるマーカー群を構成するマーカーは群毎で互いに異なる色を有しており、該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを該撮像手段で撮影することを特徴とする光学式光触覚センサを用いたマーカー情報取得方法。

[8] 請求項6, 7いずれかに記載の方法において、該マーカーを用いて各撮像装置のキャリブレーションを行うことを特徴とする光学式光触覚センサを用いたマーカー情報取得方法。

[9] 透明弾性体と該透明弾性体内に設けた複数のマーカーとから構成された触覚部と、該透明弾性体の触覚面に物体が接触した際のマーカーの振る舞いを撮影してマーカー画像を取得する複数の撮像装置とを有する光学式触覚センサにおけるマーカー画像の統合方法であって、

該画像統合方法は、

該複数の撮像装置の各撮像装置によって、各撮像装置が重複撮影領域を有するように該透明弾性体の部分領域を撮影して部分画像を取得するステップと、

該重複撮影領域内の同一マーカーが一致するように各撮像装置で取得された部分画像を統合するステップ、

を有する光学式触覚センサを用いた画像統合方法。

[10] 請求項5に記載の光学式触覚センサを用いた力ベクトル再構成法であって、

該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを撮影してマーカー画像を取得するステップと、

該マーカー画像から、求めたい力ベクトルの個数よりも多い、マーカーの振る舞いに関する情報を取得するステップと、

取得したマーカーの振る舞いに関する情報を伝達関数に入力することで、力ベクトルを出力として得るステップとを有し、

力ベクトルを得るステップは、力ベクトルの算出に寄与度の低いマーカーの振る舞いに関する情報を省いて力ベクトルを算出することを特徴とする力ベクトル再構成法。

[11] 請求項10において、力ベクトルを得るステップは、力ベクトルを求めたい位置の近傍のマーカーの振る舞いに関する情報のみを用いて力ベクトルを算出するものであることを特徴とする力ベクトル再構成法。

[12] 請求項11において、該力ベクトルを求めたい位置は、一つあるいは複数のサンプリング点から構成されていることを特徴とする力ベクトル再構築法。

[13] 請求請12において、

該力ベクトルを求めたい位置の周囲に複数の力のサンプリング点を配置するステップと、

力ベクトルを求めたい位置の近傍のマーカーの振る舞いに関する情報を用いて該力ベクトルを求めたい位置及び該力ベクトルを求めたい位置の周囲の複数の力のサンプリング点に作用した力ベクトルをそれぞれ算出するステップと、

算出された力ベクトルにおいて、該力ベクトルを求めたい位置に作用した力ベクトルのみを採用するステップと、

を有することを特徴とする力ベクトル再構成法。

[14] 請求項13において、該力ベクトルを求めたい位置の周囲のサンプリング点は、該力ベクトルを求めたい位置にあるサンプリング点から離隔するに従って疎に配置することを特徴とする力ベクトル再構成法。

[15] 請求項10において、力ベクトルを得るステップは、該伝達関数を構成する行列の要素の中で0に近い要素を省いて力ベクトルを算出するものであることを特徴とする

力ベクトル再構成法。

[16] 請求項5に記載の光学式触覚センサを用いた力ベクトル再構成法であって、

該弾性体の触覚面に物体が接触した際の該有色マーカーの振る舞いを撮影してマーカー画像を取得するステップと、

該マーカー画像から、求めたい力ベクトルの個数よりも多い、マーカーの振る舞いに関する情報を取得するステップと、

該マーカー画像から所定の大きさの小領域を設定し、該小領域内外に複数の力ベクトルのサンプリング点を配置するステップと、

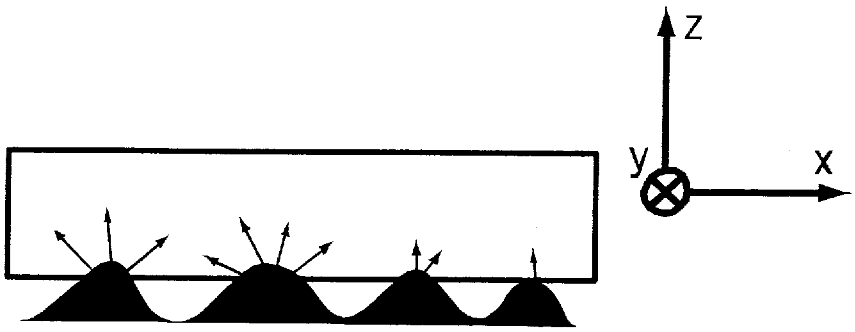
該小領域内のマーカー情報を伝達関数に与えて該複数の力ベクトルのサンプリング点に作用した力ベクトルを算出するステップと、

該小領域内に配置した複数のサンプリング点の少なくとも一部のサンプリング点に作用した力ベクトルを採用するステップと、

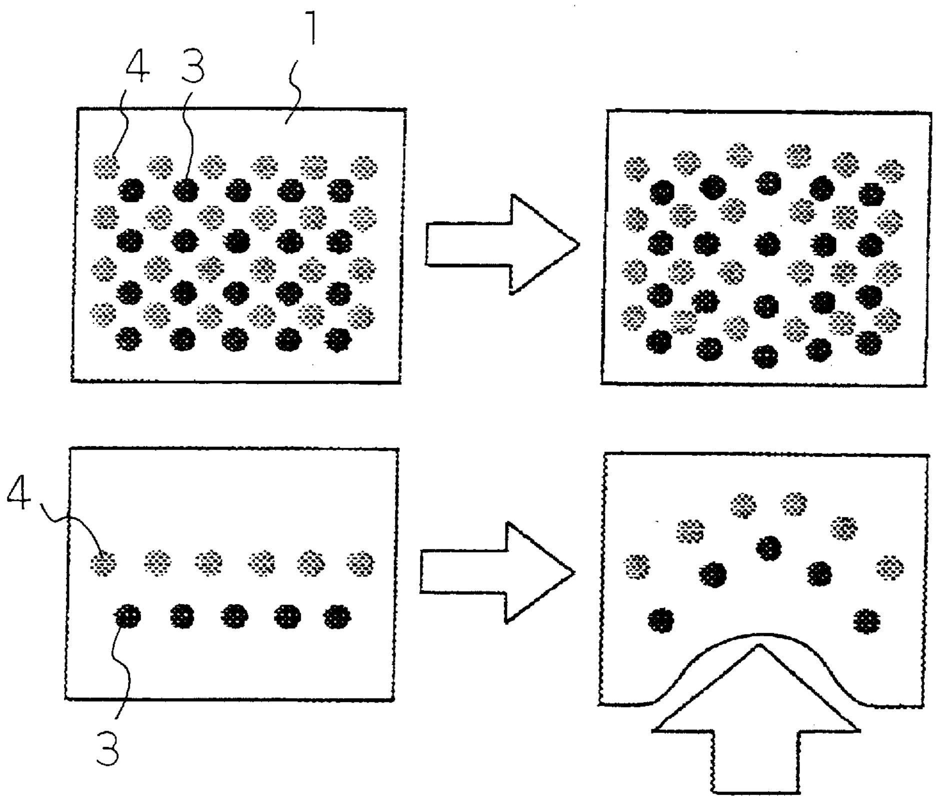
を有することを特徴とする力ベクトル再構築法。

[17] 請求項16において、サンプリング点は該小領域内で密に配置し、該小領域から離隔するに従って疎に配置したことを特徴とする力ベクトル再構築法。

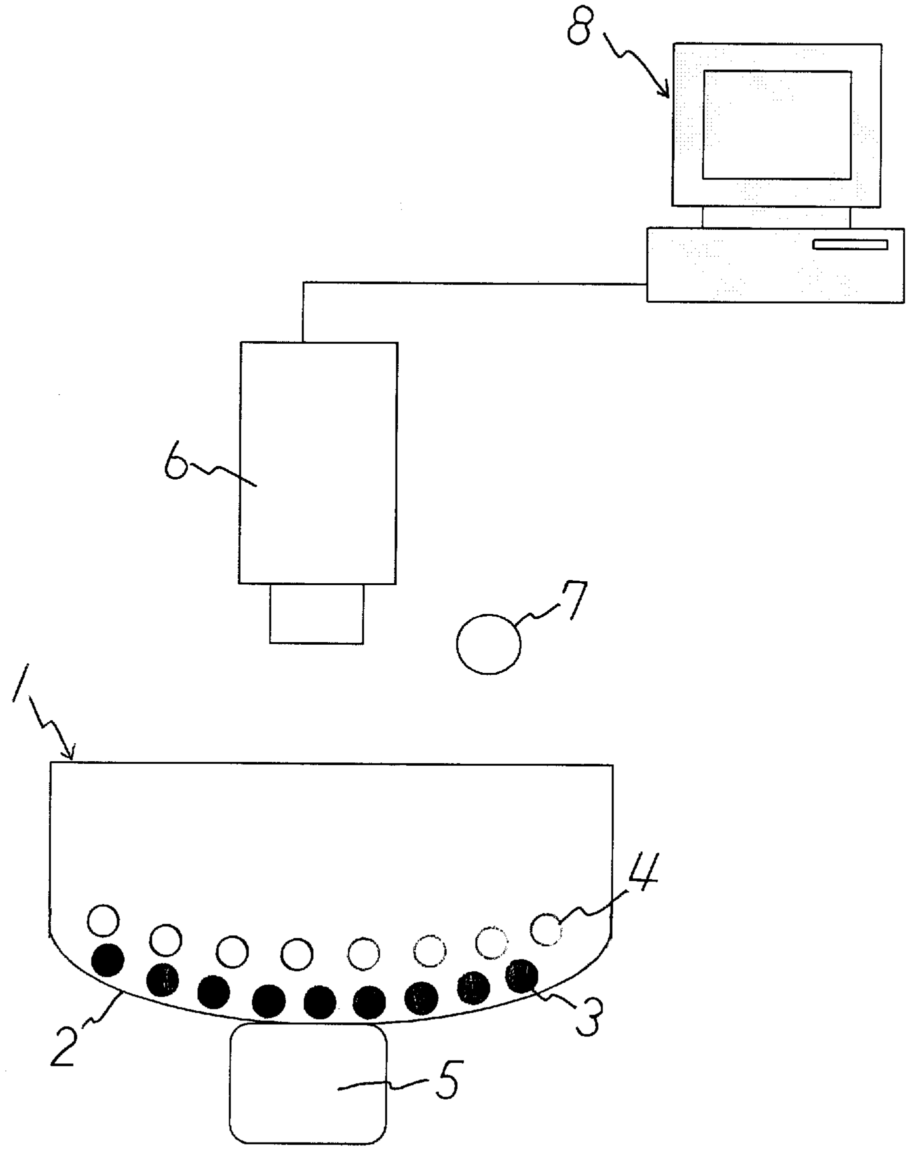
[図1]



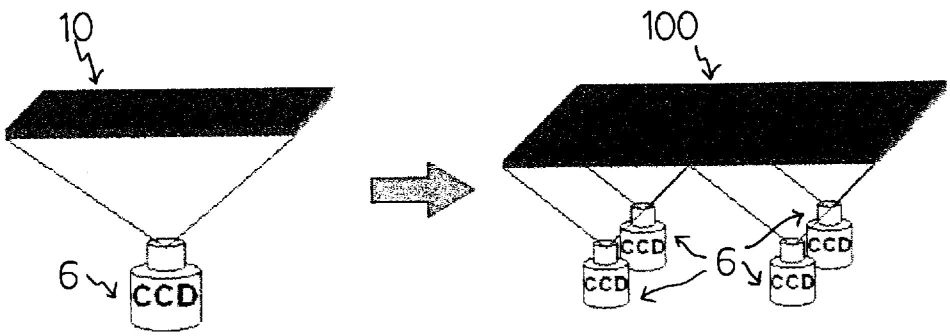
[図2]



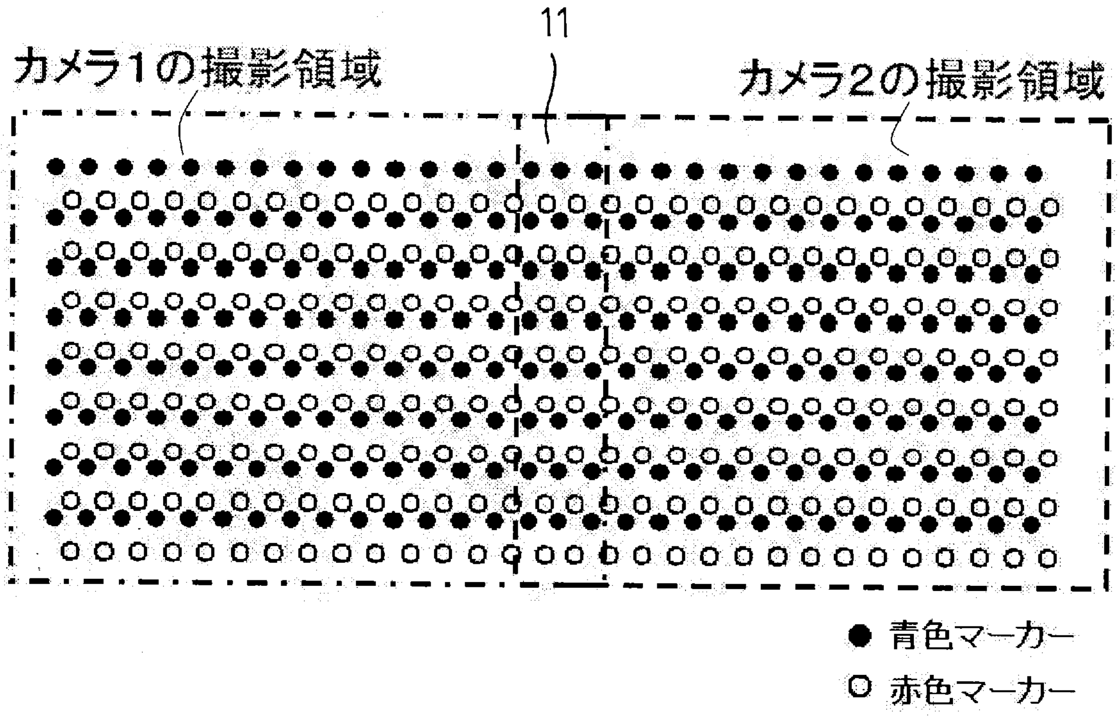
[図3]



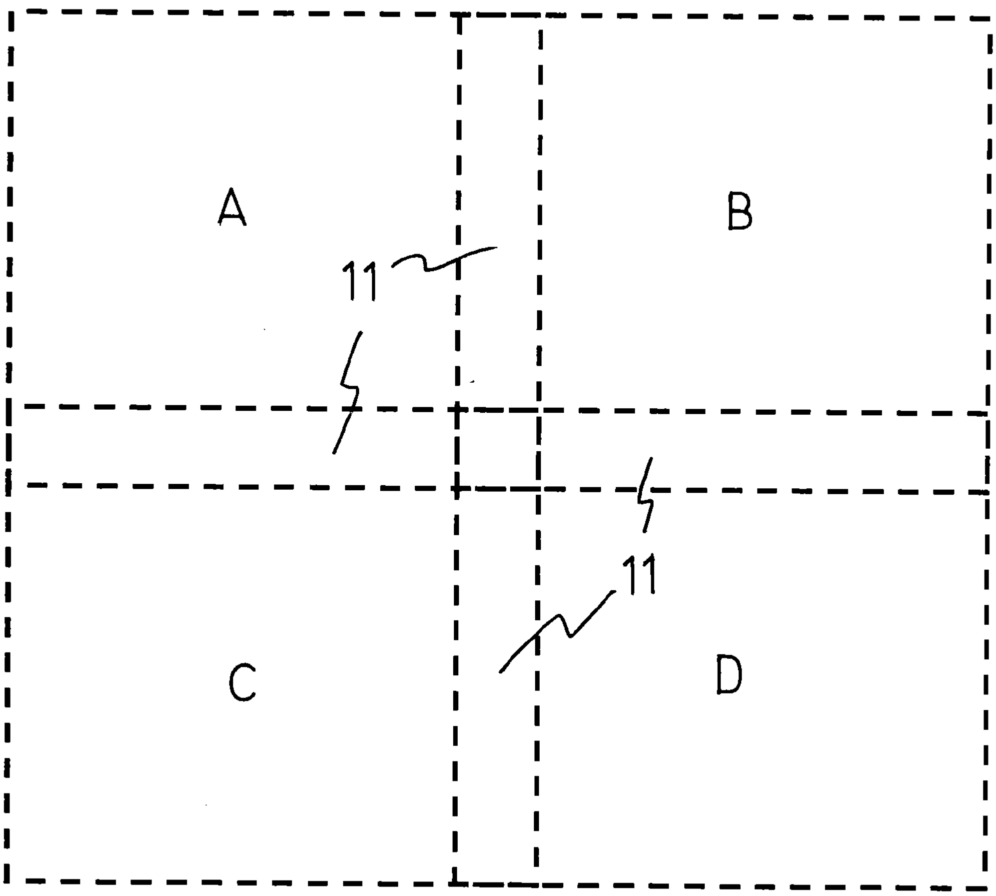
[図4]



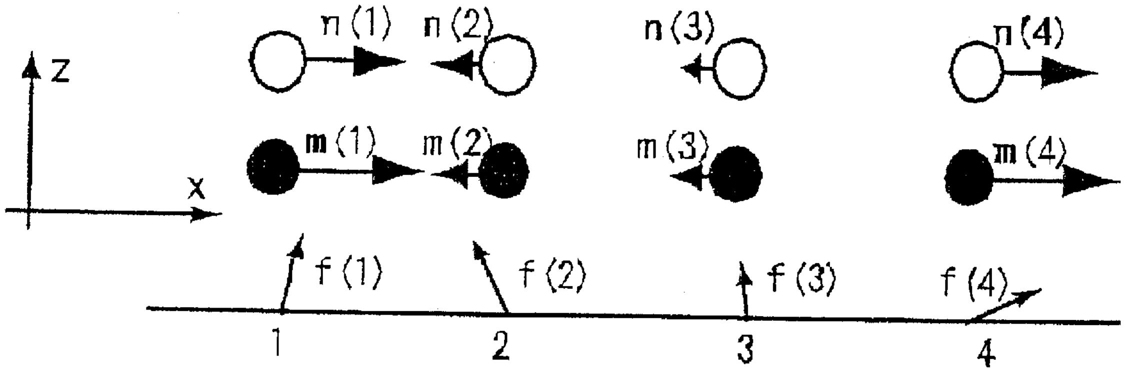
[図5]



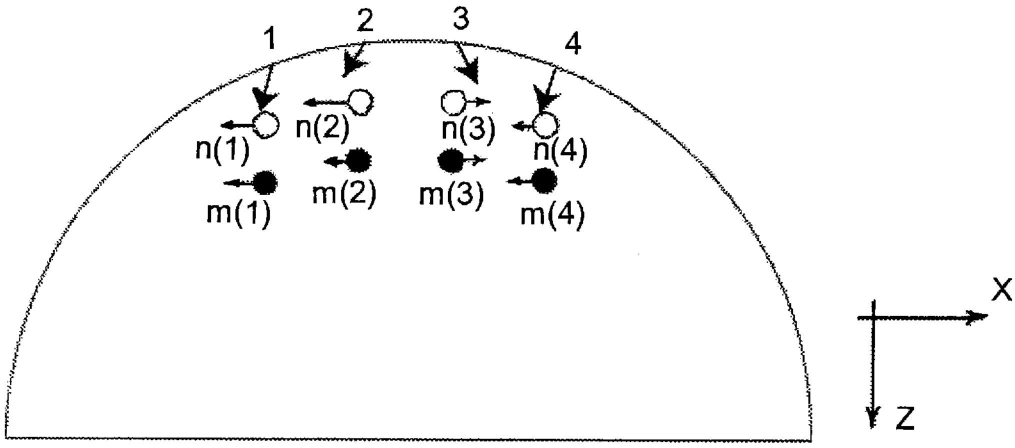
[図6]



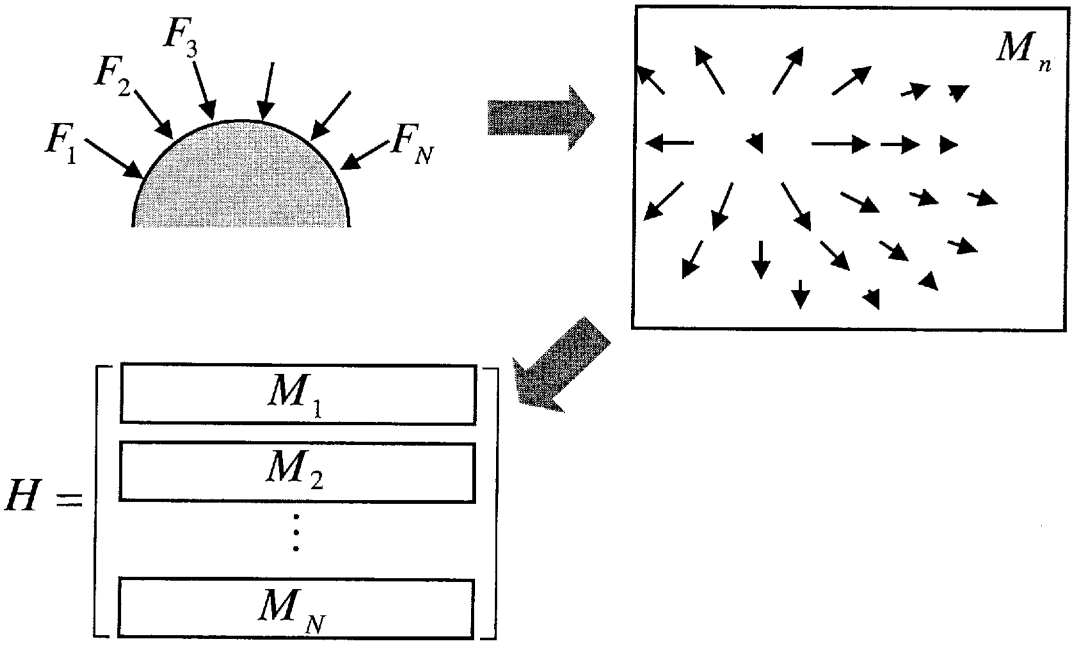
[図7]


n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
z
x
f(1)
f(2)
f(3)
f(4)
1
2
3
4

[図8]


1
2
3
4
n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
X
Z

[図9]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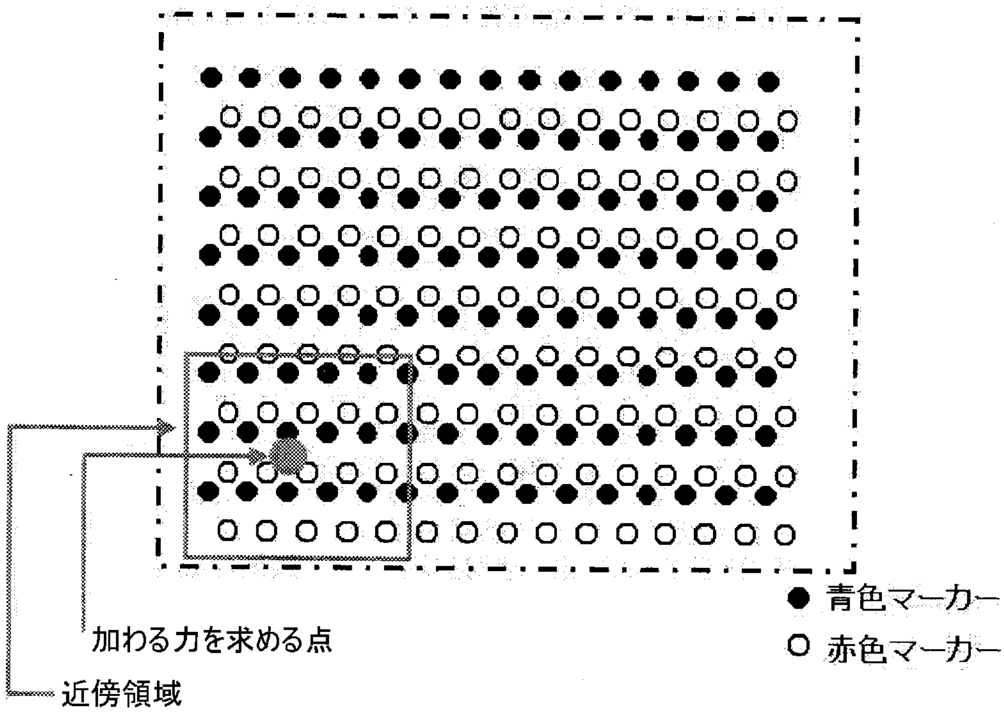
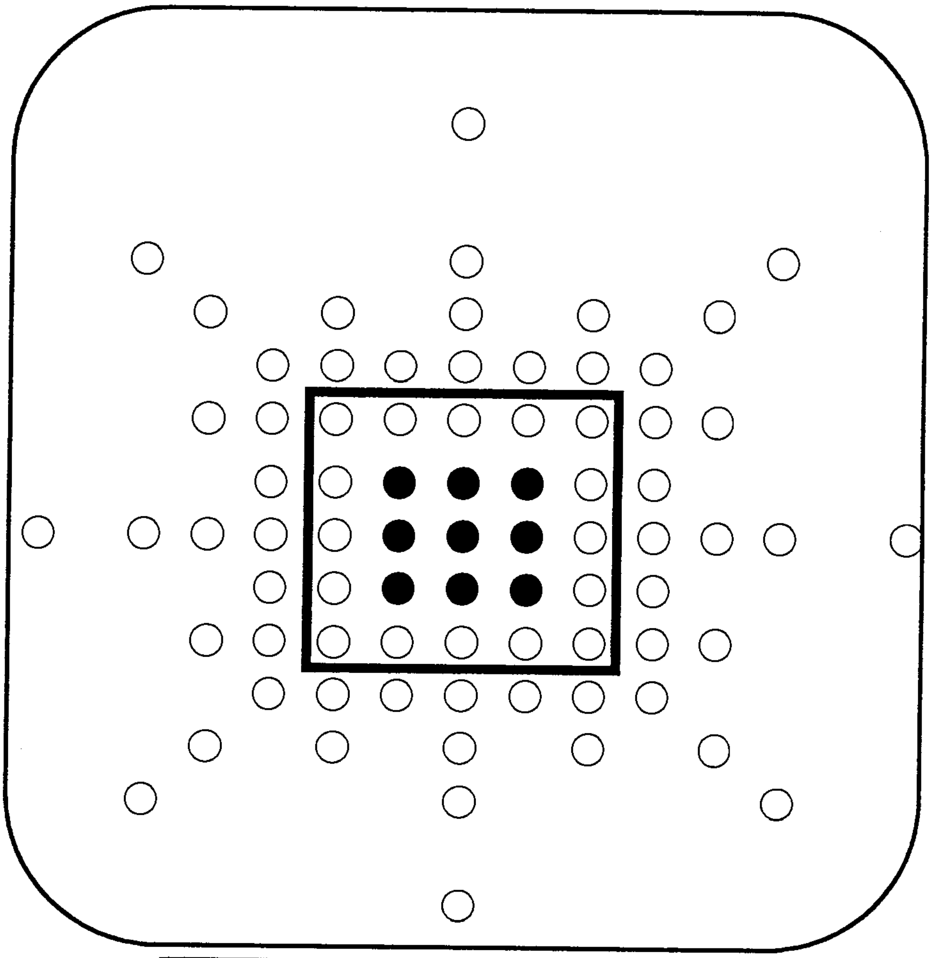
F_2
F_1
F_N
M_n
M_1
M_2
M_N
$H =$

[図10]

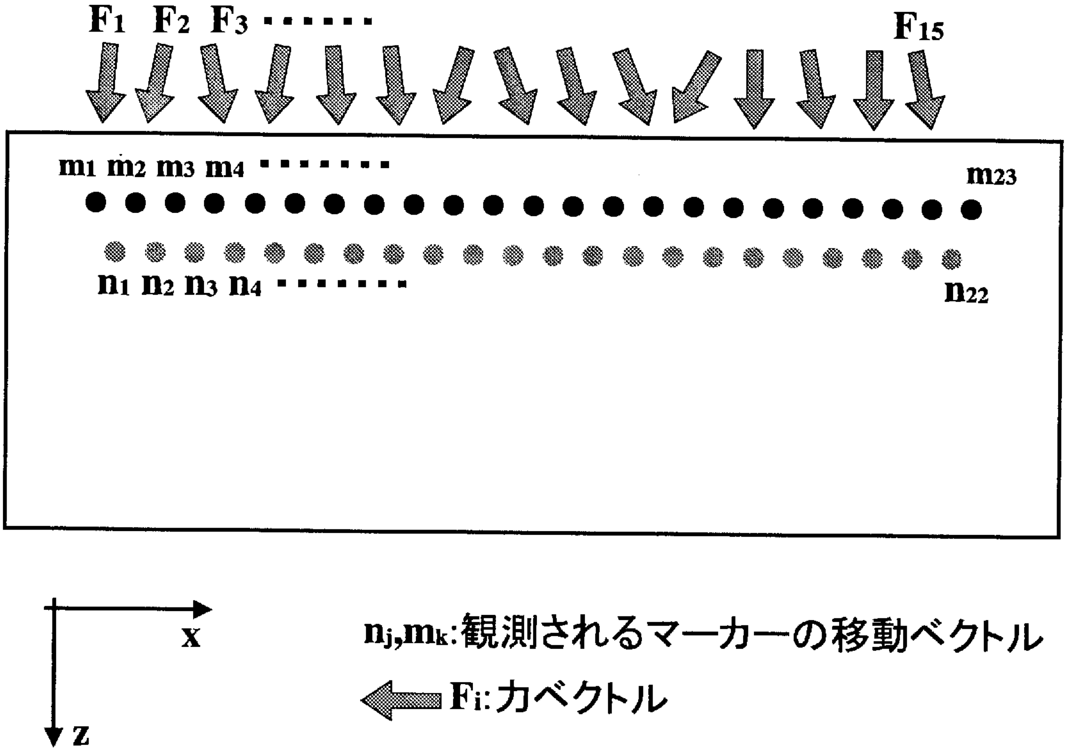


[図11]

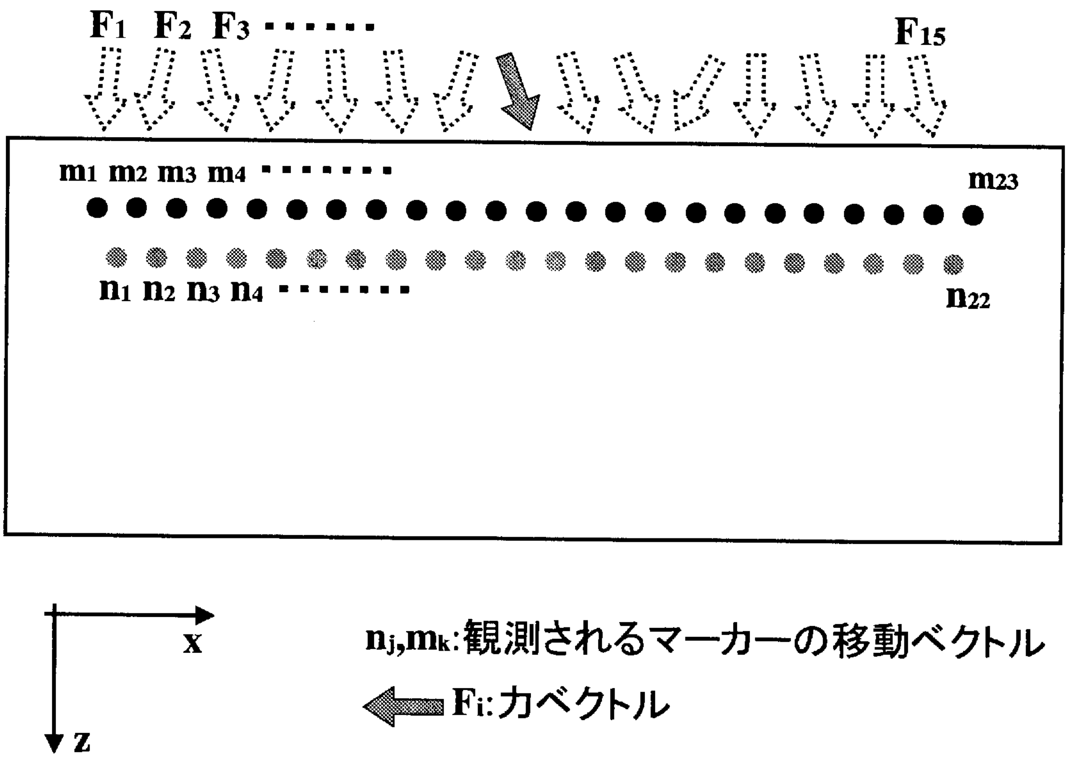


●○：力のサンプリング点
●　：計算後利用する計算結果

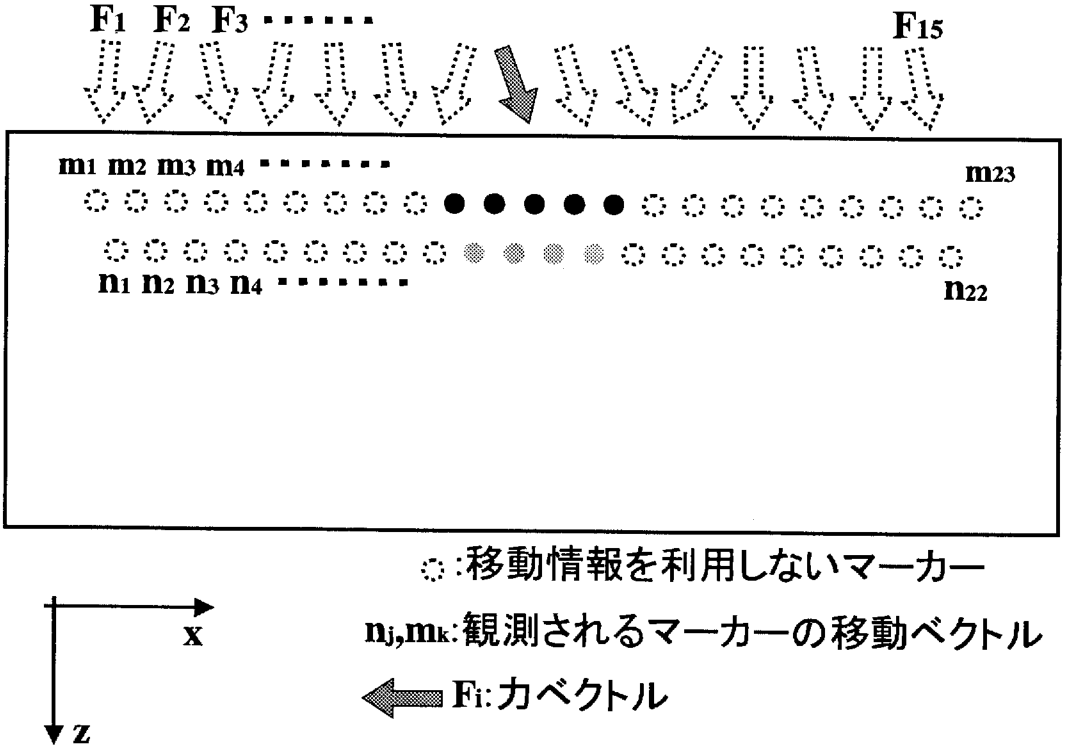
[図12]


F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk:観測されるマーカーの移動ベクトル
Fi:力ベクトル

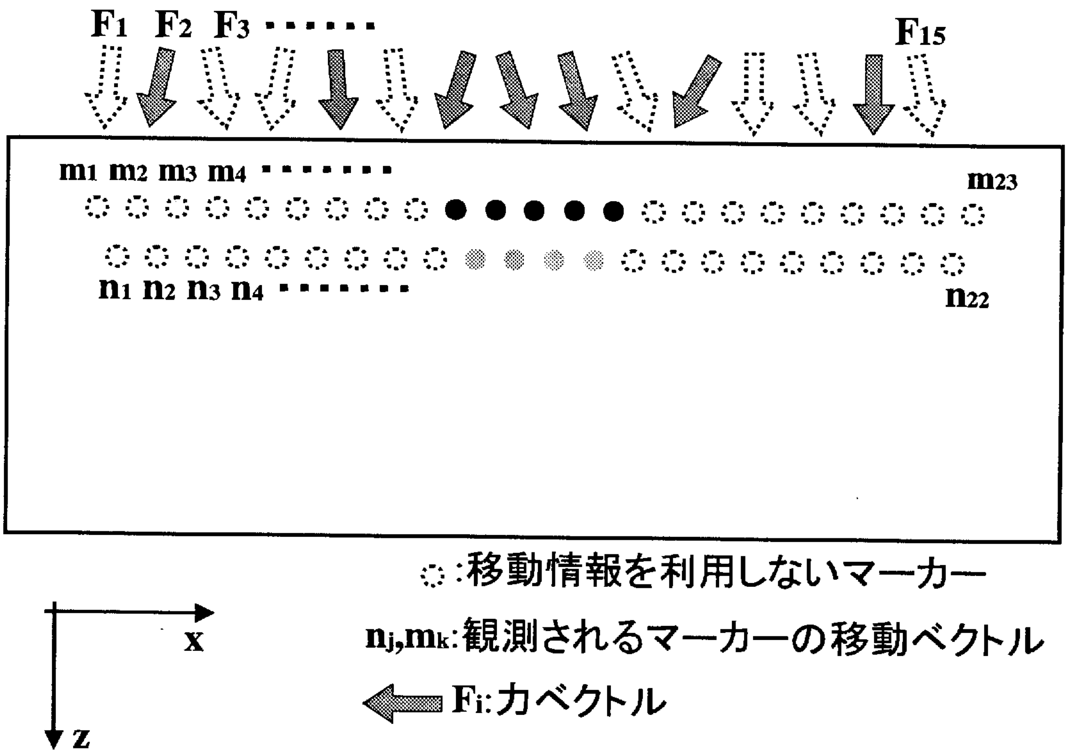
[図13]


F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk:観測されるマーカーの移動ベクトル
Fi:力ベクトル

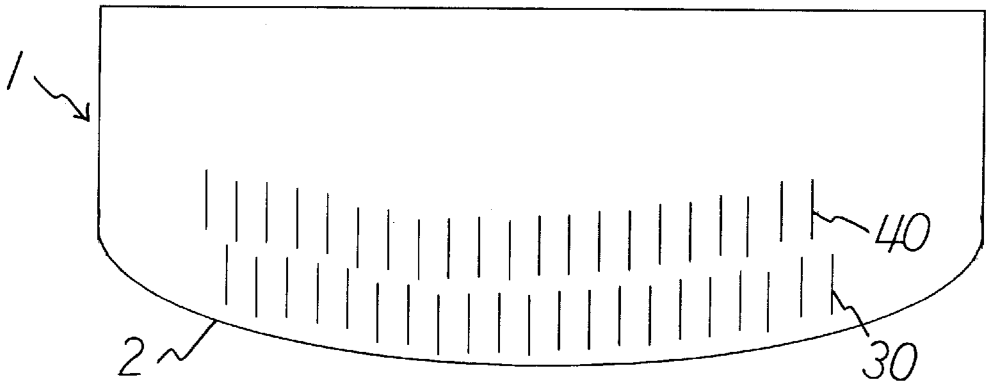
[図14]


F1 F2 F3 ······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
:移動情報を利用しないマーカー
x
nj,mk:観測されるマーカーの移動ベクトル
Fi:力ベクトル
z

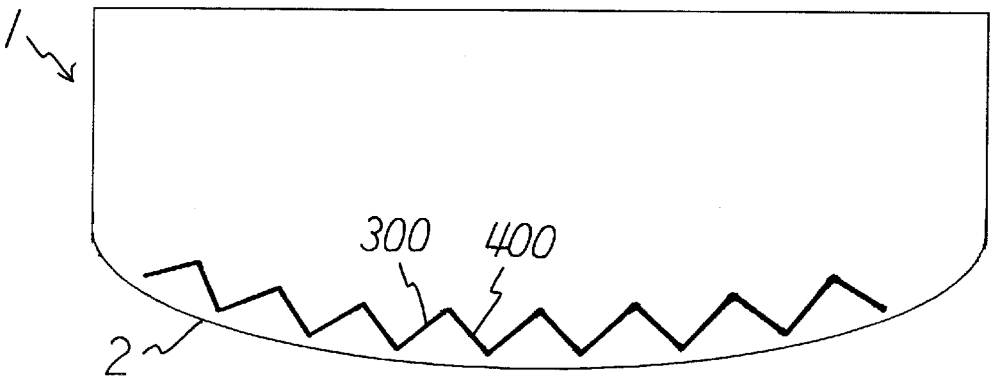
[図15]

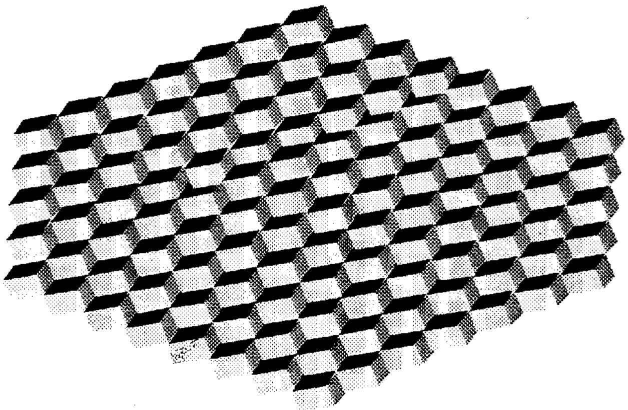

F1 F2 F3 ······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
:移動情報を利用しないマーカー
x
nj,mk:観測されるマーカーの移動ベクトル
Fi:力ベクトル
z

[図16]

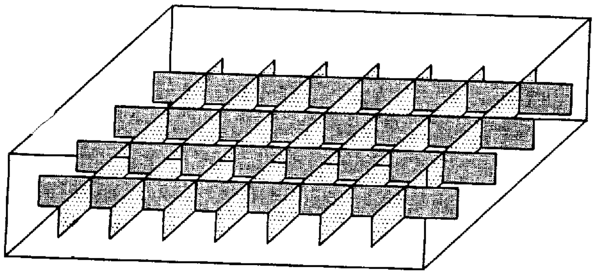


[図17]

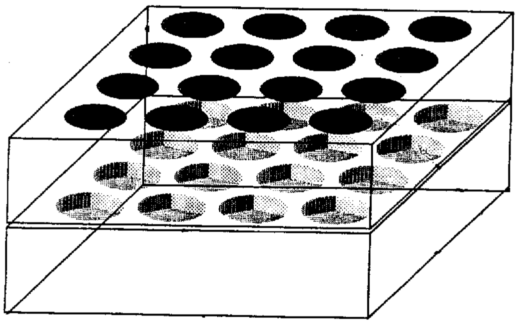




[図18]



[図19]



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2005/003650

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl^7 G01L5/16, 1/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Int.Cl^7 G01L5/16, 1/24, G03B37/00, G01C7/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2005
Kokai Jitsuyo Shinan Koho	1971-2005	Toroku Jitsuyo Shinan Koho	1994-2005

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 02/18893 A1 (Center for Advanced Science and Technology Incubation, Ltd.(CASTI)), 07 March, 2002 (07.03.02), Full text; all drawings & EP 1321753 A1 Full text; all drawings & US 2003/0178556 A1 & AU 8254901 A & CA 2419252 A1	1-17
Y	JP 7-67020 A (Olympus Optical Co., Ltd.), 10 March, 1995 (10.03.95), Par. Nos. [0018] to [0020]; Figs. 4 to 5 (Family: none)	1-17

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 May, 2005 (18.05.05)	07 June, 2005 (07.06.05)
Name and mailing address of the ISA/ Japanese Patent Office	Authorized officer
Facsimile No.	Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2005/003650

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2001-141660 A (Keisoku Kensa Kabushiki Kaisha), 25 May, 2001 (25.05.01), Par. Nos. [0008] to [0009]; Figs. 1 to 3 (Family: none)	1-17

国際調査報告

国際出願番号 ＰＣＴ／ＪＰ２００５／００３６５０

Ａ． 発明の属する分野の分類（国際特許分類（ＩＰＣ））

Int.Cl.[7] G01L5/16, 1/24

Ｂ． 調査を行った分野

調査を行った最小限資料（国際特許分類（ＩＰＣ））

Int.Cl.[7] G01L5/16, 1/24, G03B37/00, G01C7/06

最小限資料以外の資料で調査を行った分野に含まれるもの

日本国実用新案公報	１９２２－１９９６年
日本国公開実用新案公報	１９７１－２００５年
日本国実用新案登録公報	１９９６－２００５年
日本国登録実用新案公報	１９９４－２００５年

国際調査で使用した電子データベース（データベースの名称、調査に使用した用語）

Ｃ． 関連すると認められる文献

引用文献のカテゴリー＊	引用文献名 及び一部の箇所が関連するときは、その関連する箇所の表示	関連する請求の範囲の番号
Y	WO ０２／１８８９３ A1（株式会社先端科学技術インキュベーションセンター）２００２．０３．０７，全文，全図 & EP 1321753 A1, 全文, 全図 & US 2003/0178556 A1 & AU 8254901 A & CA 2419252 A1	1-17
Y	JP ７－６７０２０ A（オリンパス光学工業株式会社） １９９５．０３．１０，【００１８】－【００２０】，第４－５図 （ファミリーなし）	1-17

☑ Ｃ欄の続きにも文献が列挙されている。　　☐ パテントファミリーに関する別紙を参照。

＊ 引用文献のカテゴリー
「Ａ」特に関連のある文献ではなく、一般的技術水準を示すもの
「Ｅ」国際出願日前の出願または特許であるが、国際出願日以後に公表されたもの
「Ｌ」優先権主張に疑義を提起する文献又は他の文献の発行日若しくは他の特別な理由を確立するために引用する文献（理由を付す）
「Ｏ」口頭による開示、使用、展示等に言及する文献
「Ｐ」国際出願日前で、かつ優先権の主張の基礎となる出願の日の後に公表された文献
「Ｔ」国際出願日又は優先日後に公表された文献であって出願と矛盾するものではなく、発明の原理又は理論の理解のために引用するもの
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「＆」同一パテントファミリー文献

国際調査を完了した日 １８．０５．２００５	国際調査報告の発送日 07.6.2005
国際調査機関の名称及びあて先 日本国特許庁（ＩＳＡ／ＪＰ） 郵便番号１００－８９１５ 東京都千代田区霞が関三丁目４番３号	特許庁審査官（権限のある職員） 2F 9613 松浦 久夫 電話番号 ０３－３５８１－１１０１ 内線 ３２１６

Ｃ（続き）．　関連すると認められる文献		
引用文献のカテゴリー＊	引用文献名　及び一部の箇所が関連するときは、その関連する箇所の表示	関連する請求の範囲の番号
Y	JP ２００１－１４１６６０ A (計測検査株式会社) ２００１．０５．２５，【０００８】－【０００９】，第１－３図 (ファミリーなし)	1-17

US007659502B2

(12) **United States Patent**
Tachi et al.

(10) **Patent No.: US 7,659,502 B2**

(45) **Date of Patent: Feb. 9, 2010**

(54) **OPTICAL TACTILE SENSOR**

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(73) Assignee: **Toudai TLO, Ltd.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 440 days.

(21) Appl. No.: **10/571,370**

(22) PCT Filed: **Mar. 3, 2005**

(86) PCT No.: **PCT/JP2005/003650**

§ 371 (c)(1),
(2), (4) Date: **Mar. 9, 2006**

(87) PCT Pub. No.: **WO2005/124305**

PCT Pub. Date: **Dec. 29, 2005**

(65) **Prior Publication Data**

US 2008/0245955 A1 Oct. 9, 2008

(30) **Foreign Application Priority Data**

Jun. 16, 2004 (JP) 2004-177786

(51) **Int. Cl.**
G06M 7/00 (2006.01)
H01L 27/00 (2006.01)
G06F 3/041 (2006.01)

(52) **U.S. Cl.** **250/221**; 250/208.1; 345/173

(58) **Field of Classification Search** 250/221, 250/231.1, 216, 226, 208.1, 231.19, 559.44, 250/559.46; 345/173, 175; 356/601, 607; 73/774, 768; 901/33
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,599,908	A *	7/1986	Sheridan et al.	73/862.046
6,909,084	B2	6/2005	Tachi et al.	250/221
2003/0178556	A1 *	9/2003	Tachi et al.	250/227.11

FOREIGN PATENT DOCUMENTS

JP	7-67020	3/1995
JP	11-108630	4/1999
JP	11-118625	4/1999
JP	2001-141660	5/2001
WO	02/18893 A1	3/2002

* cited by examiner

Primary Examiner—Georgia Y Epps
Assistant Examiner—Don Williams
(74) *Attorney, Agent, or Firm*—Ladas & Parry LLP

(57) **ABSTRACT**

An optical tactile sensor and an image information integrating method capable of measuring large area force vector distribution are provided. The optical tactile sensor comprises a tactile section comprising a transparent elastic body (**1**) and a plurality of markers (**3**, **4**) provided therein, and a plurality of imaging devices (**6**, **6**) for obtaining a marker image by photographing the behavior of the markers when an object (**5**) contacts the tactile face (**2**) of the transparent elastic body (**1**). The method comprises a step of obtaining a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (**1**) using the plurality of imaging devices (**6**, **6**) such that each imaging device (**6**) has an overlapped photograph region (**11**), and a step of integrating the partial images obtained by each imaging device (**6**) such that the identical markers in the overlapped photograph region match.

17 Claims, 11 Drawing Sheets

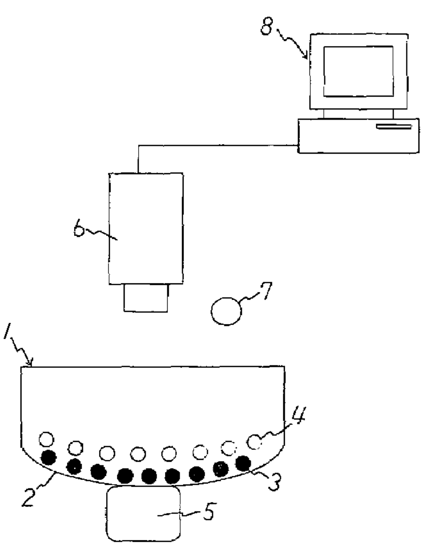


FIG.1

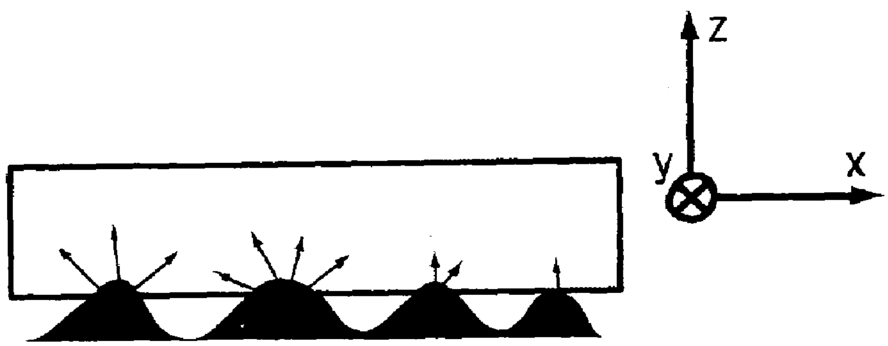


FIG.2

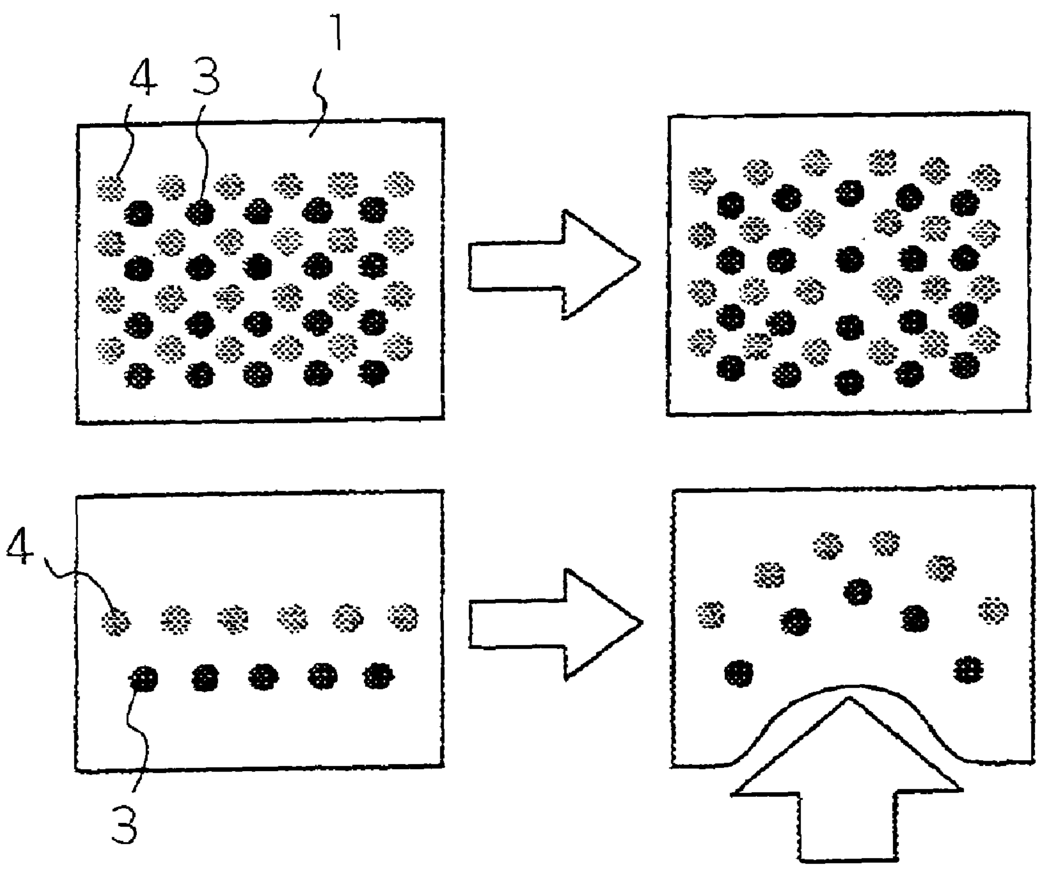


FIG.3

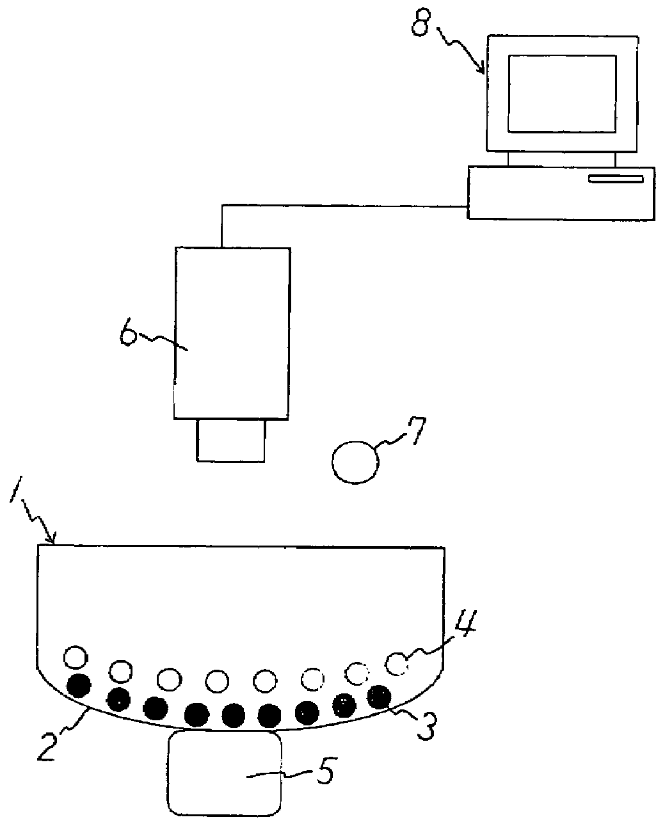


FIG. 4

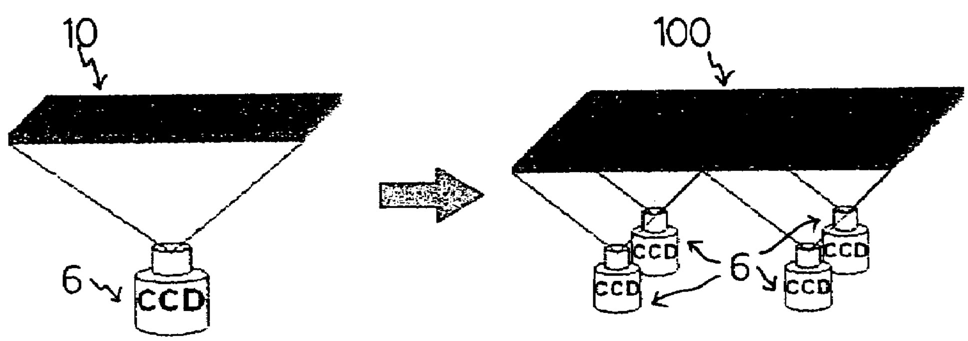


FIG.5

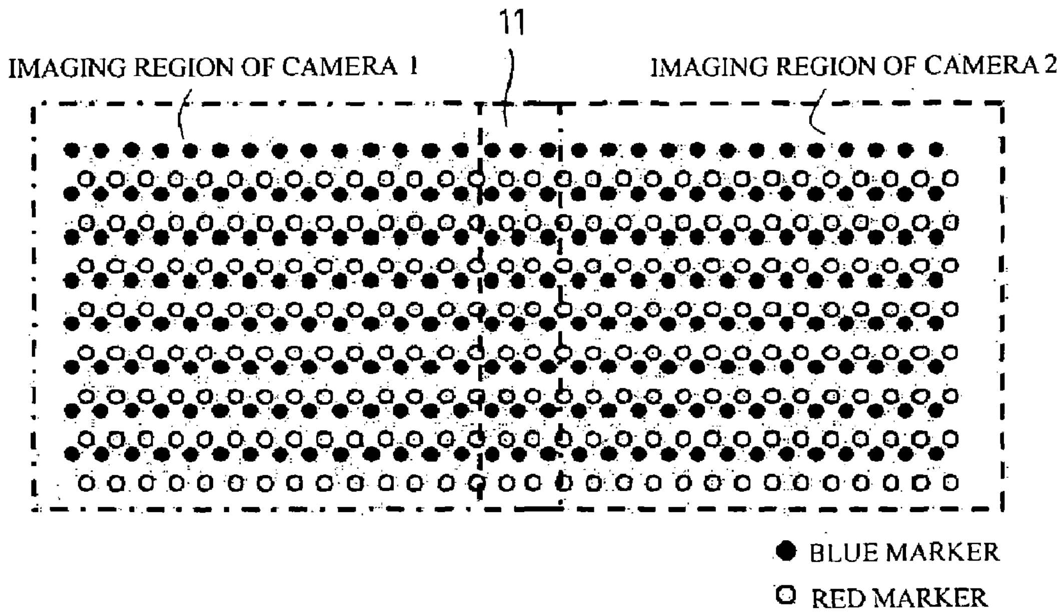

11
IMAGING REGION OF CAMERA 1
IMAGING REGION OF CAMERA 2
BLUE MARKER
RED MARKER

FIG.6

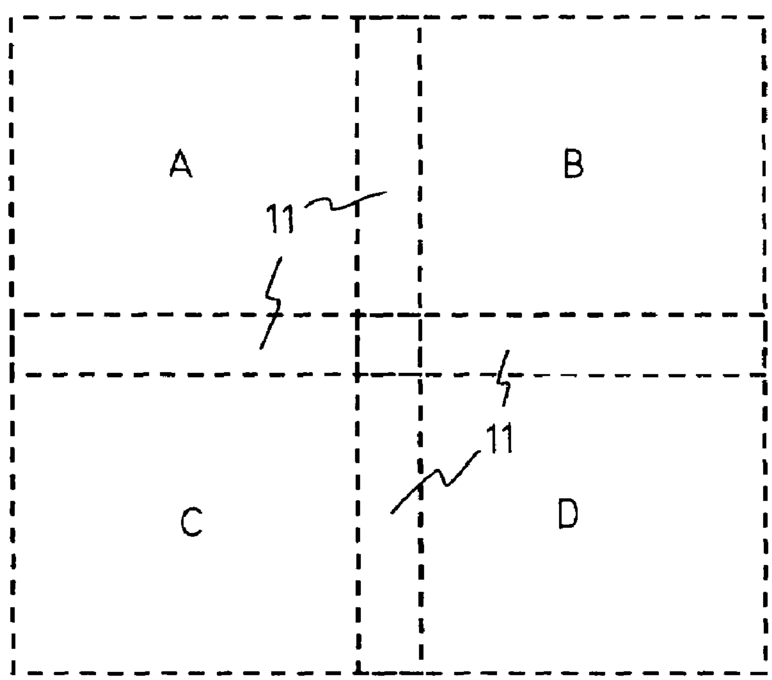

A
B
11
11
C
D

FIG.7

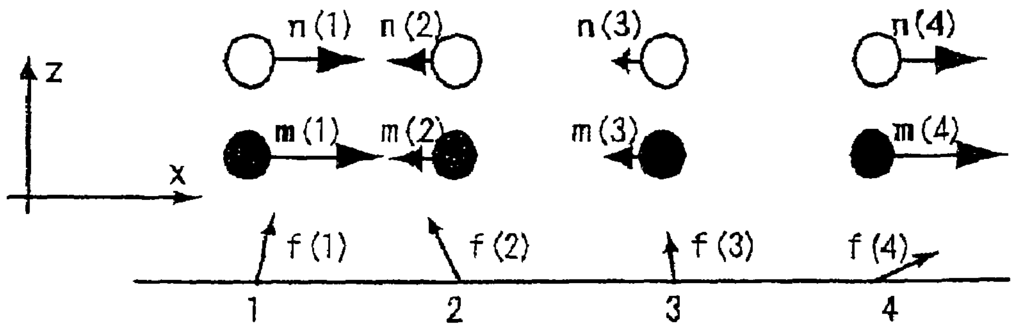

n (1)
n (2)
n (3)
n (4)
m (1)
m (2)
m (3)
m (4)
z
x
f (1)
f (2)
f (3)
f (4)
1
2
3
4

FIG.8

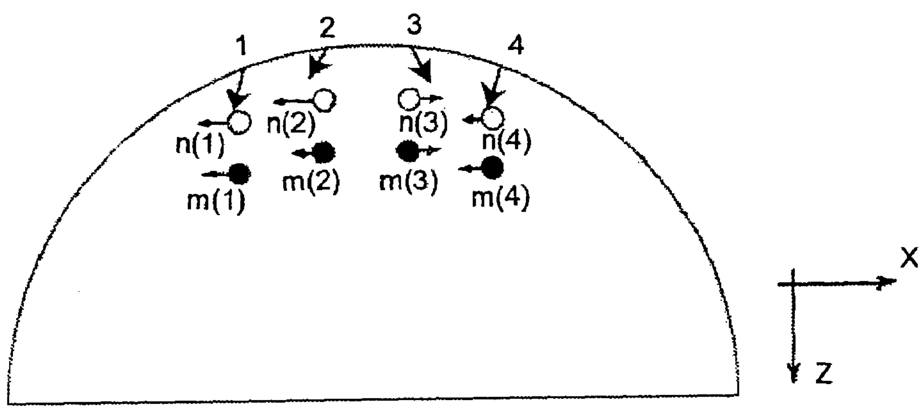

1
2
3
4
n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
X
Z

FIG.9

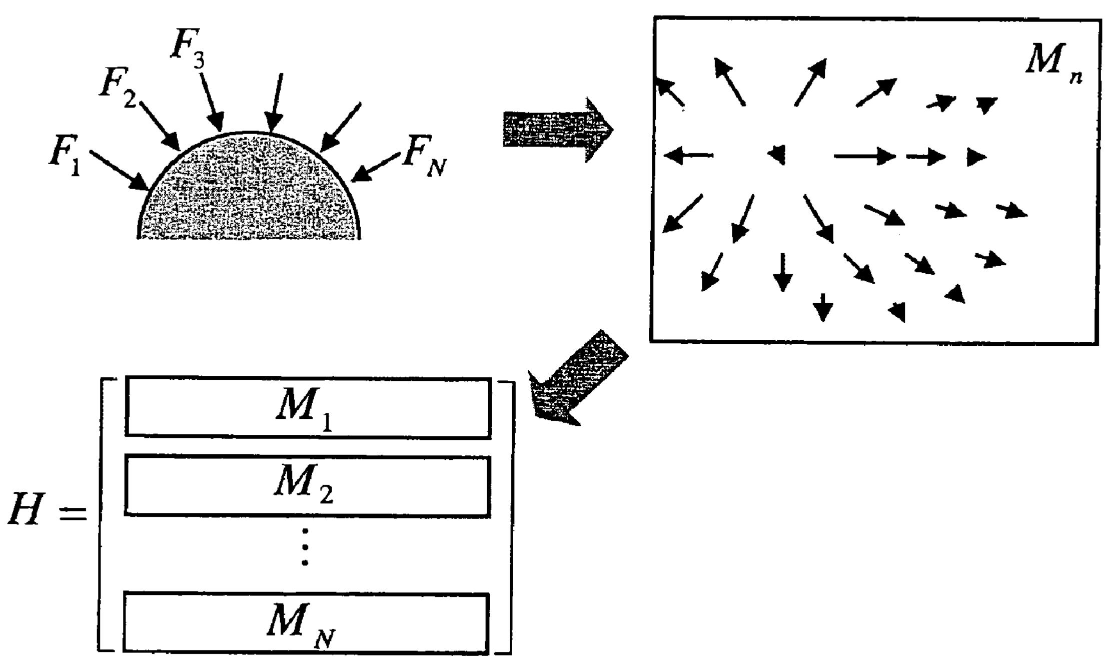


FIG.10

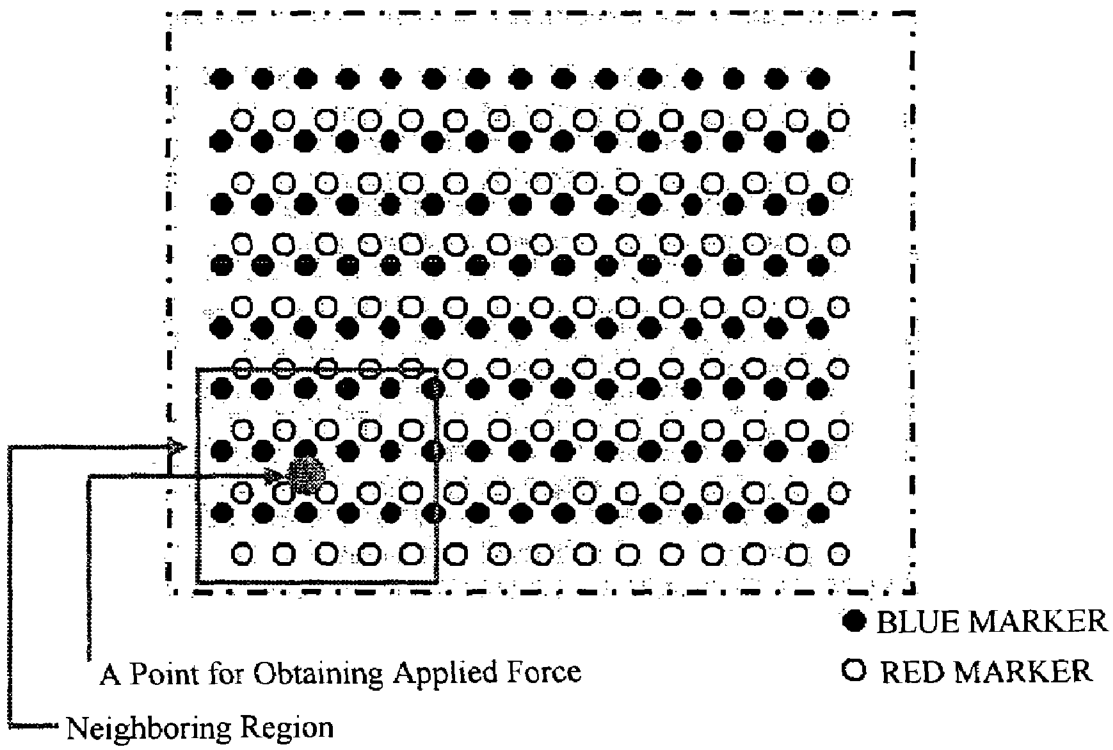
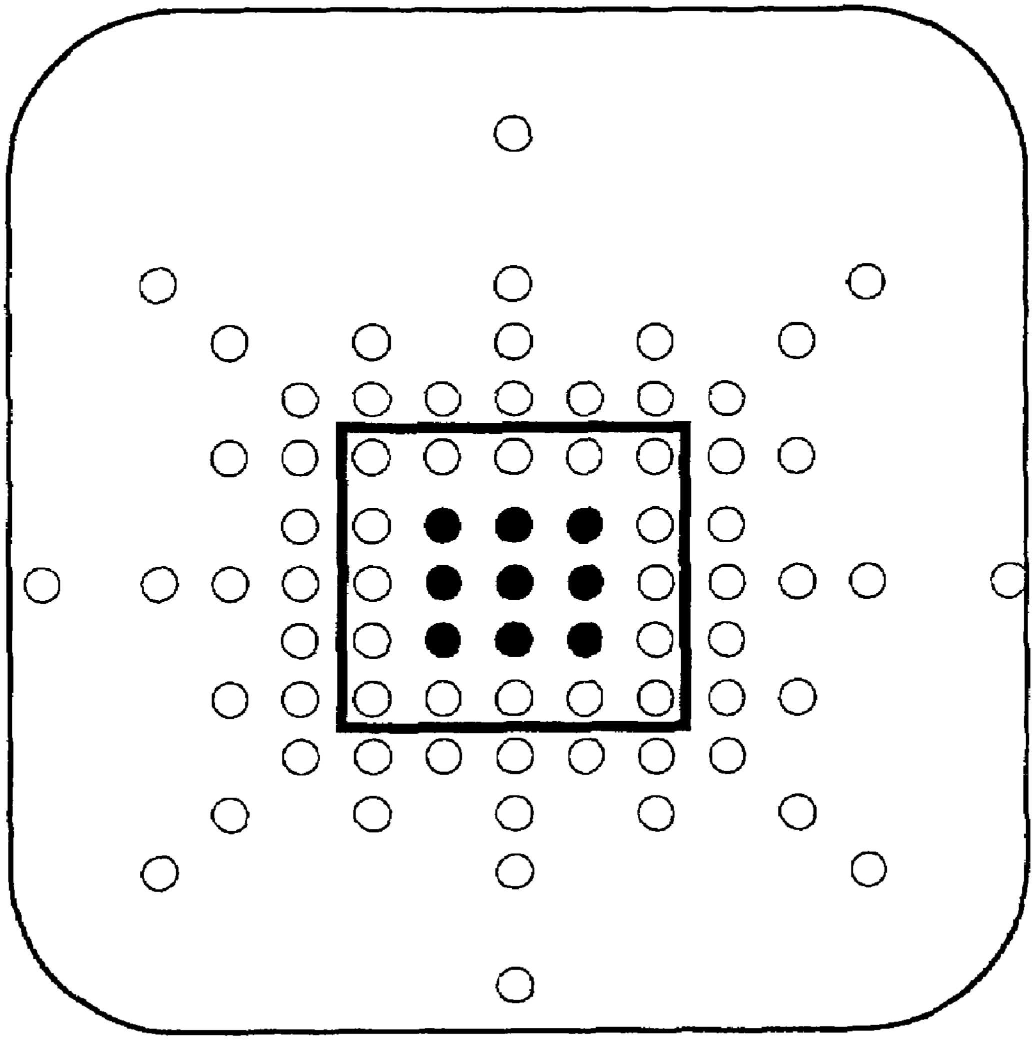

A Point for Obtaining Applied Force
Neighboring Region
BLUE MARKER
RED MARKER

FIG.11



●○ : Force Sampling Points

● : Computational Results used after computation

FIG.12

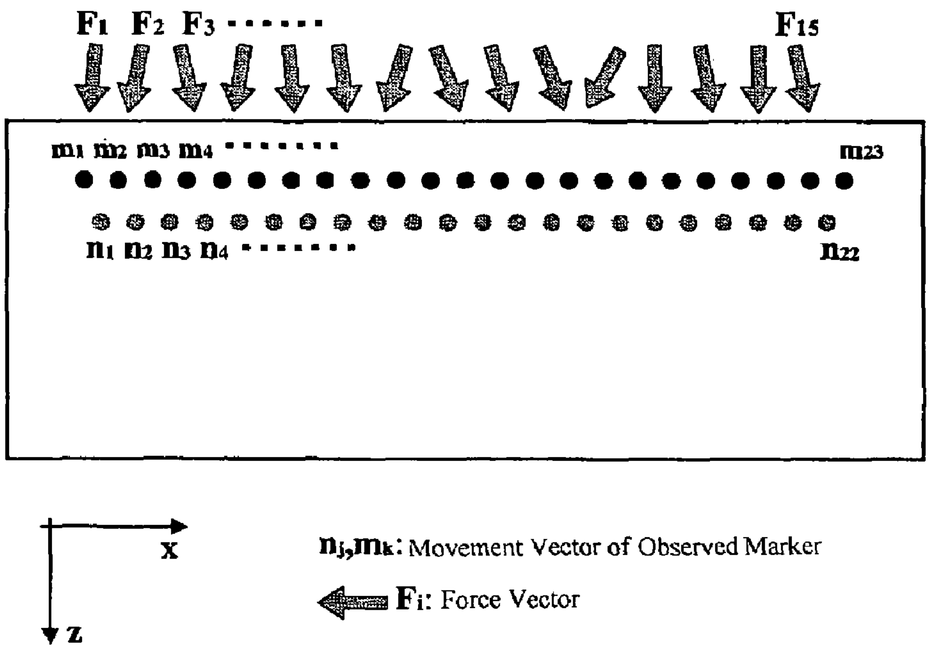

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.13

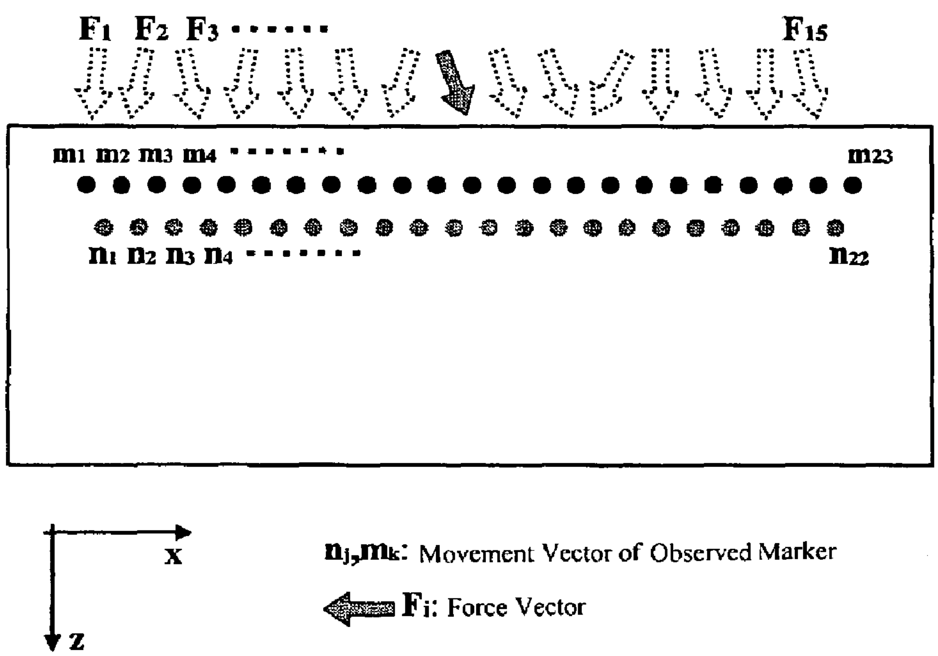

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.14

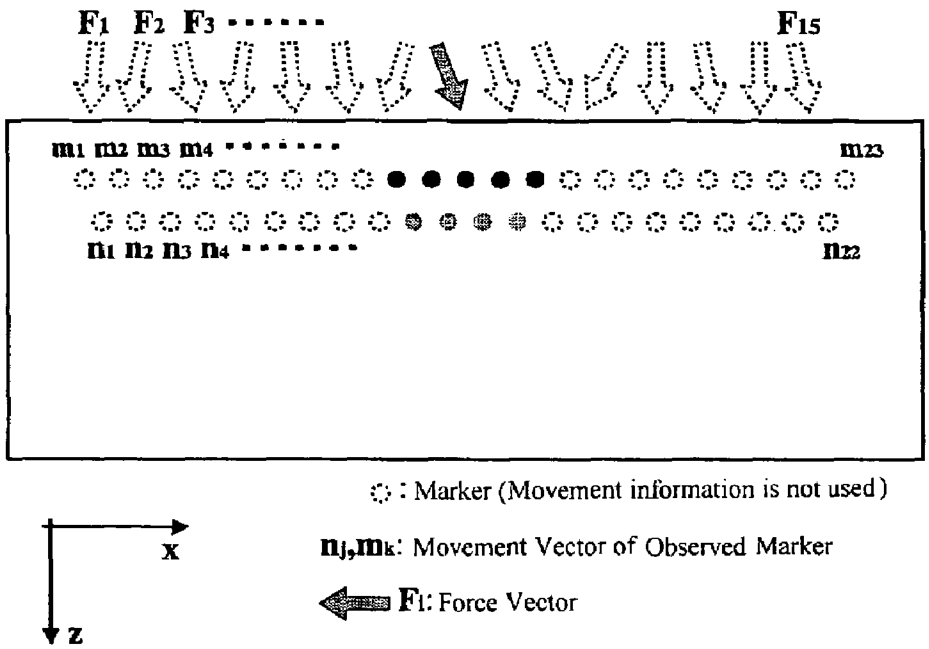

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
: Marker (Movement information is not used)
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.15

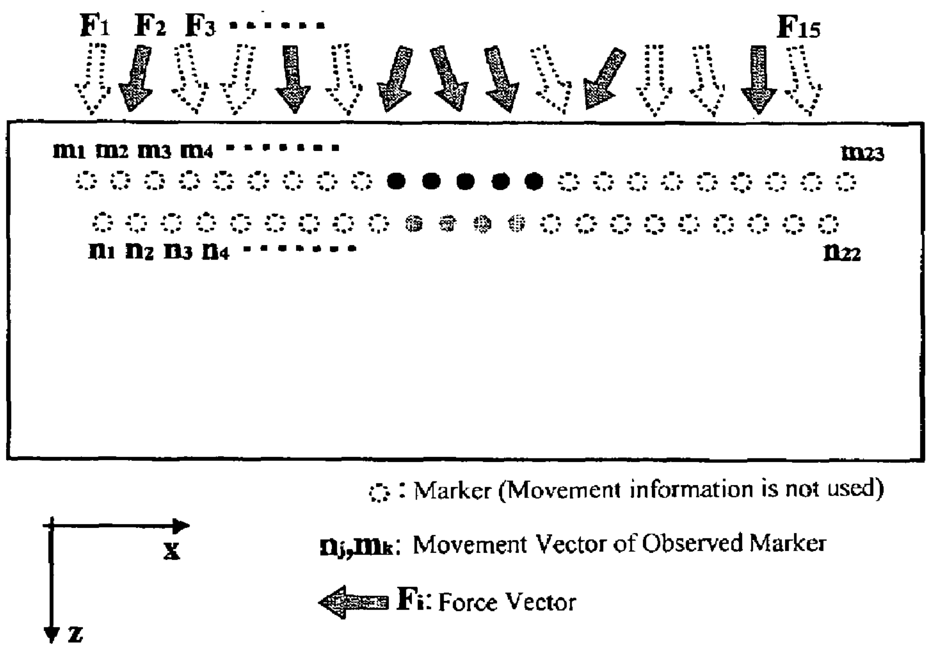

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
: Marker (Movement information is not used)
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.16

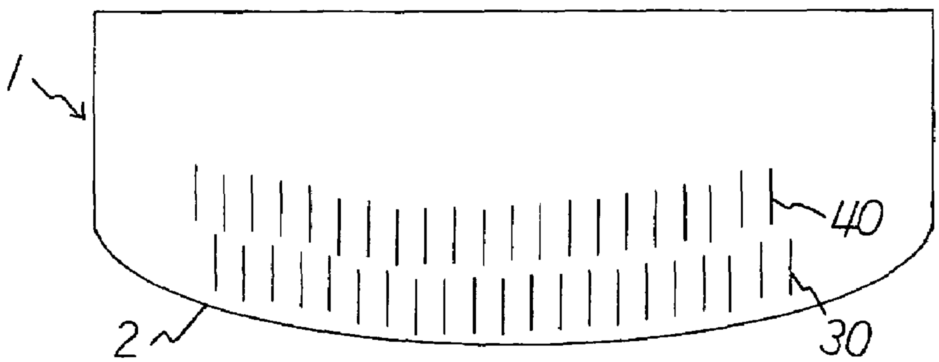


FIG.17

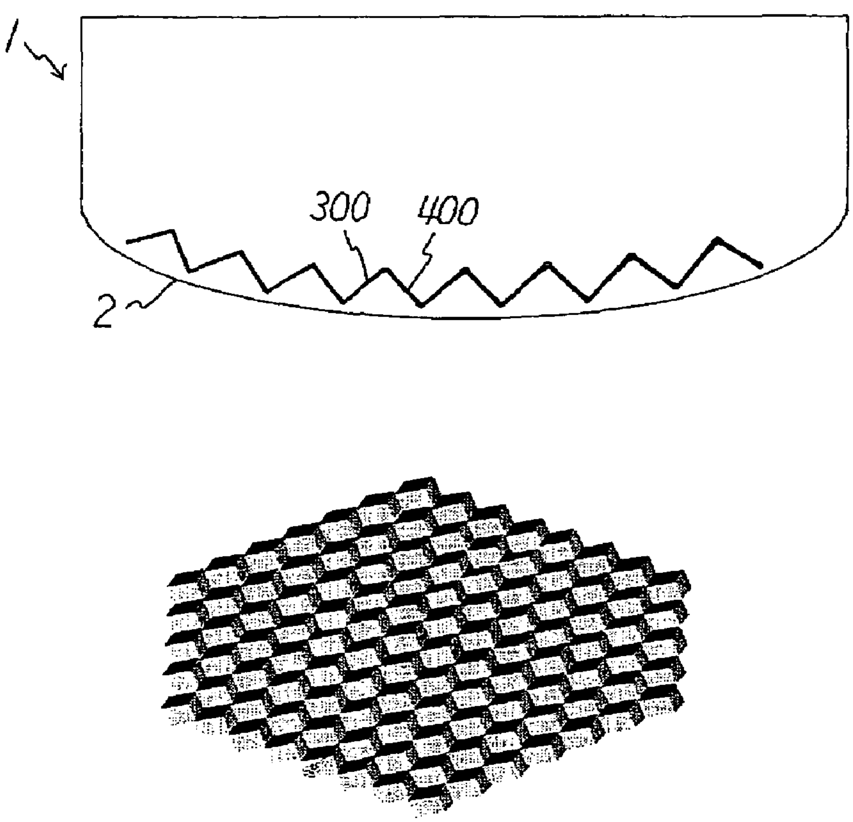


FIG.18

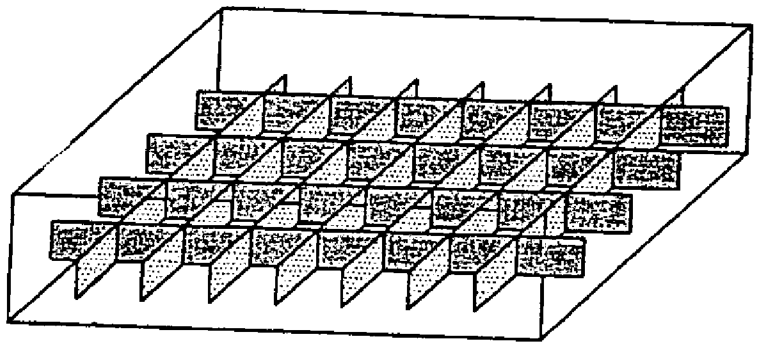
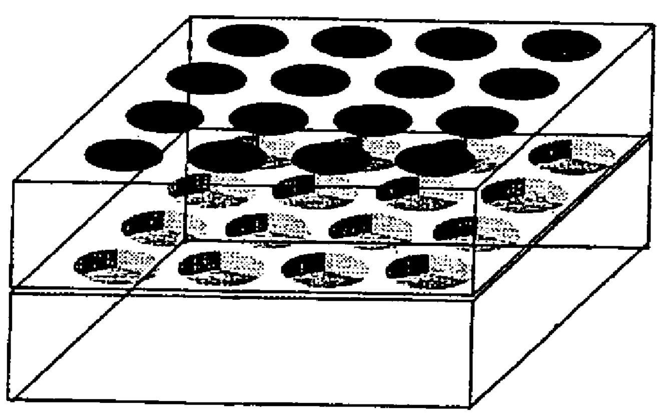


FIG.19



OPTICAL TACTILE SENSOR

FIELD OF THE INVENTION

The present invention relates to an optical tactile sensor, and preferably to a tactile sensor used for obtaining forces applied to a relatively larger area.

BACKGROUND OF THE INVENTION

When considering understanding the contact state of a contact surface using a tactile sensor, there are vectors of three components representing magnitude and direction of force acting at each point of the contact surface. This is represented as f(x,y) in the coordinate system of FIG. **1**. Here, f is a vector, and so actually has three components x, y and z at each point. When explicitly expressing each component, it is represented as f(x,y)=[fx(x,y), fy(x,y), fz(x,y)]. Since force distribution has three components at each contact point, in order to reconstruct force distribution for each contact surface using a tactile sensor, it is necessary to acquire information for each contact point on the contact surface with at least three degrees of freedom.

Some of inventors of the present invention et al. have proposed an optical tactile sensor that is capable of measuring three-dimensional force vector distribution. A principle of the optical tactile sensor will be explained based on FIG. **2**. The optical tactile sensor comprises a transparent elastic body and a CCD camera. By photographing spherical markers embedded in the transparent elastic body by the CCD camera, internal strain information of the elastic body is measured when a force is applied on the surface of the elastic body, and force vector distribution is reconstructed from the information.

By taking an image of the spherical markers by a CCD camera from z-direction where an elastic body surface is taken as the x-y plane and an orthogonal direction to the x-y plane is taken as the z-axis, movement of a point to be measured when force is applied is measured as a movement vector in the x-y plane. To reconstruct the force vector distribution from the strain information, N×N red spherical markers and blue spherical markers are arranged at different depths in the elastic body as points to be measured to obtain two sets of two-dimensional movement vectors with different depths as two pieces of different information, thereby increasing the amount of information to reconstruct the force vector distribution.

As a use for such an optical tactile sensor, initially, application to a robotic hand of a humanoid robot and so forth is considered, and as an application for an optical tactile sensor, study has focused on a small built-in type sensor. However, such an optical tactile sensor, which is capable of measuring three dimensional force vector distribution and has a sensor surface made of a elastic body, is expected to find application in a variety of fields, not only to a robotic hand.

As one of the expected applications, use of an optical tactile sensor as so called an environmental type tactile sensor can be considered. In this specification, as compared to a built-in type tactile sensor which is incorporated for use into a robotic hand or the like, a tactile sensor which is used in a fixed manner in an environment is referred to as an environmental type tactile sensor. However, with respect to an environmental type tactile sensor, which is used in a fixed manner in an environment, measurement of force distribution over a large area is expected to be necessary because such a sensor is assumed to be applied to, for example, a seating-surface of a chair, a bed, a floor, or the like. This hinders application of a conventional small optical tactile sensor, which is assumed to be incorporated in a robot hand or the like

Patent Reference: WO02/188923 A1

An object of the present invention is to provide an optical tactile sensor capable of measuring force distribution over a large area.

Another object of the present invention is to provide a marker information acquisition method and a marker image integration method capable of measuring force distribution over a large area. Still another object of the present invention is to provide a force vector reconstruction method employed in an optical tactile sensor capable of measuring force distribution over a large area.

SUMMARY OF INVENTION

The present invention has been conceived in order to solve these problems. According to the present invention, there is provided an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body. The optical tactile sensor is characterized in that the imaging means comprises a plurality of imaging devices, and each of the plurality of imaging devices is provided such that each of the imaging regions which is captured using each of the respective imaging devices has an overlapped imaging region which partially overlaps; the optical tactile sensor further comprising image integration means for integrating each of the marker images which are obtained using the plurality of imaging devices, and the image integration means integrates the imaging regions such that identical markers in the overlapped imaging regions are matched, to thereby form an integrated image.

According to one preferred aspect, the tactile section comprises a large area tactile section which is formed by combining a plurality of small area tactile sections. It should be noted that regarding the relative expressions such as a "large area" and a "small area", in this specification, a "large area" means larger compared to a tactile section such as is to be incorporated into a robotic hand, while a "small area" means smaller compared to a "large area". While a seating surface of a chair, a bed surface, a floor surface, and so forth may be listed as examples of a "large area", objects that are smaller than these items are also included in what is referred to by a "large area".

Further preferably, the tactile sensor comprises a unit comprised of one small area tactile section and one imaging means corresponding to the small area tactile section. The tactile sensor is formed by combining a plurality of the units. Formation of the tactile sensor using sensor units enables creation of a tactile section having a desired area.

The present invention employs another technical means including a method for obtaining a marker image using an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and an imaging means for obtaining a marker image by photographing behavior of a marker when an object contacts the sensing surface of the transparent elastic body. The method of obtaining marker information comprises a step of providing a plurality of imaging devices as the imaging means and obtaining a partial marker image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region, and a step of forming an integrated marker image by integrating the partial marker images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

The present invention employs still another technical means including a method for integrating a marker image, which is employed in an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and a plurality of imaging devices for obtaining a marker image by photographing behavior of a marker when an object contacts the sensing surface of the transparent elastic body. The image integration method comprises a step of obtaining a partial image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region, and a step of integrating the partial images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

As a construction of the tactile portion, preferably, the tactile section comprises a transparent elastic body and a plurality of groups of markers provided inside the elastic body, each marker group being made up of a number of colored markers, with markers making up different marker groups having different colors for each group. The imaging device takes an image of the behavior of colored makers in the transparent elastic body when an object contacts the surface of elastic body.

Also, the present invention includes calibration of each imaging means while using a sensing marker. As the present invention comprises a plurality of imaging devices, calibration of the imaging means is required. As the present invention has a sensing marker as an essential component, the marker can also be used as a calibration marker. Further, the present invention also includes a method for reconstructing a force vector while using such an optical tactile sensor. When a force vector is calculated without the data on the behavior of a marker with less contribution to the force vector calculation, time for force vector calculation can be reduced.

According to the present invention, as the information on the behavior of a marker is obtained using a plurality of imaging means, even a tactile section having a large area can be preferably handled. Therefore, use of a sensor according to the present invention makes it possible to measure force vector distribution over a large area, which in turn makes it possible to determine a force applied to a sensing surface having a large area, based on the obtained marker information. Moreover, as a sensing marker can be used for integration of the image data obtained by the imaging means and calibration of the respective imaging means, the sensor can be formed using a reduced number of components.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a drawing showing force vector distribution exerted between a tactile sensor and an object to be contacted.

FIG. **2** is a drawing showing the principle of an optical tactile sensor. The upper diagram is a plane view (CCD image) of a transparent elastic body, while the lower diagram is a side view of the transparent elastic body. The transparent elastic body has two kinds of marker groups embedded therein. When force is applied to the transparent elastic body from beneath, the marker moves from what is shown in the left diagram to what is shown in the right diagram.

FIG. **3** is a schematic diagram showing an optical tactile sensor according to the present invention.

FIG. **4** is a schematic diagram explaining enlargement of the area of a sensor surface. The left diagram shows one unit comprising one CCD camera and an elastic body section, while the right diagram shows the result of area enlargement combining units.

FIG. **5** is a diagram for showing a method for integrating the image data which is obtained using a plurality of imaging means.

FIG. **6** is a schematic diagram showing image data which is obtained using the sensor shown in FIG. **4**.

FIG. **7** is a diagram explaining a force vector applied to a contact surface (plane surface) and movement of the marker.

FIG. **8** is a diagram explaining a force vector applied to a contact surface (free curving surface) and movement of the marker.

FIG. **9** is a diagram explaining a method for creating a transfer function for use in reconstruction of force vector distribution.

FIG. **10** is a diagram showing an integrated image captured using a plurality of cameras and explaining a method for reducing the time for calculation necessary for reconstruction of a force vector, in which, when a force applied to a point is obtained, data on only the markers located in its vicinity are used in the calculate of the force.

FIG. **11** is a conceptual diagram explaining an improved manner of the calculation reduction method. In the drawing, black and whit circles represent sampling points for force, and the black circle shows a result of calculation to be used after the calculation.

FIG. **12** is a diagram showing an increased number of markers.

FIG. **13** is a diagram showing an increased number of markers, in which movement of a marker caused relative to the force applied to one point is focused.

FIG. **14** is a diagram explaining the speed increasing method shown in FIG. **10**, based on FIG. **13**.

FIG. **15** is a drawing explaining an improved method, based on FIG. **13**.

FIG. **16** is a diagram showing another embodiment of a marker (cylindrical marker).

FIG. **17** is a diagram showing another embodiment of a marker. The upper diagram shows a stepwise band marker, while the lower diagram shows a pyramidal marker.

FIG. **18** is a diagram showing another embodiment of a marker (crossing strip marker).

FIG. **19** is a diagram showing another embodiment of a marker (color-discriminated plane marker).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[A] Basic Construction of Optical Tactile Sensor

An optical tactile sensor of the present invention comprises a sensing section and imaging means. The tactile section comprises a transparent elastic body and a plurality of marker groups provided in said body, each marker group being comprised of a number of colored markers, with markers constituting different marker groups having different colors for each group. The imaging means is provided to take an image of behavior of colored markers when the surface of elastic body is contacted by an object to obtain marker images. A force applied to the surface is reconstructed from information as to the behavior of markers that is obtained from the marker images.

At least one of displacement, strain and inclination of the colored markers when the elastic body contacts an object is observed by photographing behavior of the colored markers. Strain information inside the transparent elastic body is detected from information about the behavior colored markers when a contact object contacts the sensor, and the shape of the contact object calculated from strain information, and information about force acting on a contact interface (including both the elastic body surface and the contact object surface) are also detected. According to the present invention, it is possible to separately collect a plurality of types of information with a simple method called "color coding", and it is possible to acquire a plurality of types of tactile information at the same time with an optical system. According to the present invention, independent observed information (information as to behavior of markers) whose number is equal to or greater than the number of unknowns are collected using color coding, and it is possible to estimate and reconstruct force vectors by stably resolving an inverse problem.

The colored markers are photographed by photographing device, in a preferred example, a CCD camera, and image processing is carried out by a processor. For example, an image at the time of body contact and an image of a previous condition (a condition where external force is not acting on the transparent elastic body) are compared, and an amount of movement of the markers is detected. Alternatively, the markers are embedded in the transparent elastic body in such an arrangement that they can not be recognized normally (in a state where external force is not acting on the transparent elastic body), and a configuration is such that markers are recognized in response to displacement deformation and inclination of markers caused by strain in the vicinity of positions where each of the markers exist when an object contacts the transparent elastic body, and information is detected from the appearance of the colored markers. In another preferable aspect, the behavior of markers (step-like strip markers, for example) can be obtained by variance of marker intensity.

The optical tactile sensor stores a transfer function by which force vectors or force vector distribution applied to the surface of the elastic body are reconstructed from information (movement vectors of each marker when an object contacts the surface, for example) obtained by photographing device as to behavior of markers. The transfer function is a function that associates force information applied to the surface of the sensor with information as to the behavior of markers (movement vectors, for example). The image information of markers is obtained by photographing the colored markers when the object contacts the sensing surface of the elastic body, and the information as to the behavior of markers is obtained from the image information of markers. The force vector is obtained as an output by inputting the obtained information to the transfer function. The number of information as to the behavior of markers that is input to the transfer function is more than the number of force vectors to be obtained.

The transfer function, depending on the shape of the elastic body, may be obtained based on an equation derived from theory of elasticity. However, when the surface of elastic body is an arbitrary curved surface, preferably, the transfer function is obtained by measurement or simulation. The transfer function by measurement or simulation can be obtained from information (movement vectors, for example) as to behavior of markers when x-directional force, y-directional force, and z-directional force having predetermined magnitude, for example, are applied to sampling points arranged on the surface of the sensor.

Referring to FIG. 3, the construction of an optical tactile sensor of the present invention is shown. The sensor comprises a transparent elastic body **1** formed of a transparent elastic material and a curved surface **2**, or a surface for sensing. The transparent elastic body **1** is provided with a plurality of colored markers **3**, **4** embedded in the transparent elastic body **1** in the vicinity of the surface **2** and along the curved surface **2**. A sensing section is comprised of the transparent elastic body **1** and the colored markers **3**, **4** arranged inside the elastic body.

The colored markers **3**, **4** are comprised of two groups of colored markers and the two marker groups are embedded in different depths respectively from the surface **2**. Colored markers **3** constituting one marker group and colored markers **4** constituting the other marker group have different colors to each other. For example, one marker group consists of a plurality of blue markers **3** and the other marker group consists of a plurality of red markers **4**.

When an object **5** comes into contact with the transparent elastic body **1**, the colored markers **3**, **4** provided inside the transparent elastic body **1** are moved due to the internal strain of the elastic body. The sensor is also provided with a camera **6** as a photographing device and a light source **7**. The optical camera **6** is arranged at a position on an opposite side to where an object **5** contacts so that the transparent elastic body **1** is provided between the optical camera **6** and the object **5**, and behavior or movement of the markers **3**, **4** is photographed by the camera **6**. The light source **7** may transmit light through a waveguide such as an optical fiber for example. Images of markers **3**, **4** obtained by camera **6** as imaging means are transmitted to a computer **8** and the marker images are displayed on a display. The processor of the computer **8** calculates the marker information (movement vectors as movement information, for example) regarding the behavior (displacement, strain or inclination) of markers. The processor reconstructs the distribution of forces applied to the surface **2** by an object **5** using the marker information (movement information, for example) and a transfer function that is stored in the memory device of the computer **8**.

The transparent elastic body **1** is preferably made of silicone rubber, but it can also be made from another elastic material such as another type of rubber or elastomer. The markers are preferably made from an elastic material, and more preferably made from the same material as the transparent elastic body **1**. In one preferred embodiment, the colored markers are formed by adding pigment to silicone rubber. Since deformation of the elastic body should not be inhibited by the markers, the markers are also preferably made from an elastic material (preferably having the same elastic constant as the elastic body). The material of the markers is not particularly limited as long as the extent to which deformation of the elastic body is inhibited is sufficiently small. It is also possible for a part of the elastic body to constitute the markers.

With the present invention, a plurality of optical markers are distributed within the transparent elastic body **1**, and information about a contacting object and information about displacement and deformation within the elastic body produced by contact are detected by photographing situations where displacement, deformation and inclination arise in the markers due to deformation of the elastic body **1** as a result of the object coming into contact with the elastic body **1** using a camera. FIG. **3** shows two marker groups, but the number of marker group is not limited, and three marker groups may be located in a layered manner along the surface **2**.

A camera, as a photographing device, is a digital camera, namely a camera for outputting image data as electrical signals, and in one preferred example is a CCD camera. It is also possible to use, for example, a digital camera using a C-MOS type image sensor. If three types of markers are prepared in red, green and blue, there are two methods of perceiving these three colors individually. The first method is to use color filters for separation where each marker can be regarded as being individually photographed directly by looking at RGB output from the camera. The second method is a method where imaging elements perceive only light intensity and light sources of red green and blue are prepared. When red is shone, light is only reflected from the red markers while the red light is absorbed by the markers of the other two colors, and so the camera effectively only perceives the red markers. If this is also carried out at separate times for green and blue, information equivalent to that using the first method can be acquired.

[B] Environment Type Tactile Sensor

An embodiment of an environmental type tactile sensor according to the present invention will be described. An environmental type tactile sensor comprises a plurality of sensor units. As shown in the left diagram in FIG. **4**, a sensor unit comprises one small area tactile section **10** and one CCD camera **6** which serves as an imaging means for photographing the small area tactile section **10**. As described above in connection with a basic structure, the small area tactile section **10** comprises a transparent elastic body and colored markers provided inside the transparent elastic body. When an object contacts the sensing surface of the transparent elastic body, the colored markers provided inside the transparent elastic body move, and the CCD camera **6** photographs the movements of the colored markers. Then, as shown in the right diagram in FIG. **4**, a plurality of sensor units are combined to form a sensor surface having a large area. By carpeting the small area tactile sections **10** so as to form the same plane such that the edges of the tactile sections abut to one another, a large area tactile section **100** is formed. The small area tactile section **10** shown has a square shape in a plane view. Although the shape of the small area tactile section is not limited to square, a square tactile section is advantageous when a plurality of small area tactile sections are carpeted. Also, although a small area tactile section having a plane sensing surface **10** is shown in the drawing, the sensing surface **10** is not limited to plane. A sensing surface having an arbitrary curved surface is also applicable.

As a plurality of CCD cameras **6** are used, integration of the image data obtained using the respective cameras **6** is necessary. FIG. **5** is a diagram explaining integration of the images obtained using a plurality of cameras. Such an image is displayed, for example, on a display of a computer **8**. Initially, using a plurality of cameras **6**, images of the small area tactile section **10** are taken such that the respective photograph regions partially overlap to one another. Thereafter, the respective images from the cameras are integrated such that the markers in the overlapped photograph regions **11** are matched, thus integrating image data. In FIG. **5**, a black circle represents a blue marker, while a white circle represents a red marker, and the photograph regions of the camera **1** and the camera **2** have an overlapped photograph region **11**. The blue and red markers within a region corresponding to the overlapped photograph region **11** in the photograph region for the camera **1** and those within a region corresponding to the overlapped photograph region **11** in the photograph region for the camera **2** are matched to one another, whereby the partial images captured using the camera **1** and **2** respectively are integrated. It should be noted that although a spherical marker is referred to here, a marker in other shapes such as is described later can be similarly used for image integration.

An image captured using four CCD cameras shown in FIG. **4** is shown in FIG. **6**. Supposing that the respective photograph regions photographed by the respective CCD cameras are referred to as A, B, C, and D, the photograph regions A, B, C, and D are integrated such that overlapped photograph regions **11** are resulted in Regions A and B, Regions A and C, Regions B and D, and Regions C and D, respectively. It should be noted that markers are omitted from FIG. **6**. Each camera is configured so as to photograph the behavior of the markers located in a region allocated in advance to the camera, and the respective allocated regions have mutually overlapped regions. According to one aspect, each of the respective cameras is set in advance so as to photograph a predetermined partial region of the transparent elastic body, and configured such that integration of the images of the respective predetermined partial regions obtained using the respective cameras enables formation of the entire image of the transparent elastic body.

Calibration of a camera to be applied when a plurality of imaging means (CCD cameras) are used is described. Generally, camera calibration is applied for correction of distortion caused in the captured image due to the lens and also for determination of the position and orientation of the camera in the world coordination system. Occurrence of distortion due to a lens is inevitable when a wide lens is used. The position and orientation of the camera is most accurately determined when using image data. In this tactile sensor, as correlation between the image data and the actual position needs to be determined, it is necessary to apply camera calibration. Generally, in a measurement system using a plurality of cameras, the following procedure needs to be followed. Initially, a stripe or black-white tile pattern with known pattern intervals is placed in a position which is known relative to the world coordination system, and the pattern is photographed. Then, displacement from an image which would be captured when the lens had no distortion is calculated using the captured image, and the lens distortion and the position and orientation of the camera are determined. Here, in an environmental type tactile sensor which similarly employs a plurality of cameras, the stripe or black-white tile pattern with known pattern intervals is already arranged in a known position as a colored marker for sensing and ready to be acquired as an image. Therefore, camera calibration, which originally needs to be conducted before assembly of the measurement system can be conducted anytime after the assemblage.

[C] Method of Reconstructing Force Vector Distribution on Sensing Surface

To obtain force vector distribution applied to a surface of the sensor from obtained information (movement vectors of markers, for example) as to behavior of markers by an optical tactile sensor, a transformation from information (movement information, for example) M as to the behavior of markers to force information F is required. The transformation from the marker information M to the force information F is obtained by an equation F=HM. Referring to FIG. **7** and FIG. **8**, a method of reconstructing the force vector distribution from the marker information will now be described based on a method of obtaining the force vector distribution from the movement vectors of markers. FIG. **7** and FIG. **8** are substantially the same except that FIG. **7** shows a plane sensing surface while FIG. **8** shows an arbitrary curved sensing surface. Here, though, for the purpose of simplification, only two-dimensional section (y-axial direction is omitted) is considered, an algorithm is the same for a general three-dimensional space.

Reference f refers to a force vector applied to a contact surface, and references m and n refer to a movement vector of a blue marker and movement vector of a red marker in the CCD element. Discrete finite points (four points in FIG. **7** and FIG. **8**) are considered. As foregoing, force vector distribution has three components (x component, y component and z component), but only two components (x component and z component) are considered. Generally, taking an image by a camera means a projection of a three-dimensional object to a pixel plane of a two-dimensional plane so that marker movements only in the horizontal direction (x component and y component) are projected in the plane. Here, marker movement only in x direction component is observed.

Here, eight components, f=[fx(**1**), fx(**2**), fx(**3**), fx(**4**), fz(**1**), fz(**2**), fz(**3**), fz(**4**)] are force vector distribution to be obtained, where m=[m(**1**), m(**2**), m(**3**), m(**4**)] and n=[n(**1**), n(**2**), n(**3**), n(**4**)] are movement vectors to be measured. The vectors m and n are represented as X. Namely, X=[m(**1**), m(**2**), m(**3**), m(**4**), n(**1**), n(**2**), n(**3**), n(**4**)]. Here, movement vectors m and n that are observed when a unit force (magnitude of 1) in the x-direction is applied to a point **1** are represented as Mx(**1**).

Namely, Mx(**1**)=[m(**1**), m(**2**), m(**3**), m(**4**), n(**1**), n(**2**), n(**3**), n(**4**)] when f=[1, 0, 0, 0, 0, 0, 0, 0].

Similarly, a movement vector of each marker when a unit force in the z-direction is applied to a point **1** are represented as Mz(**1**), a movement vector of each marker when a unit force in the x-direction is applied to a point **2** are represented as Mx(**2**), and so on. In case of a linear elastic body where linear summation relationship holds between applied forces and strains (most elastic bodies meet this characteristics), movement vectors are represented as

$$X=Mx(1)\times fx(1)+Mz(1)\times fz(1)+Mx(2)\times fx(2)+\ldots+Mz(4)\times fz(4),$$

when general forces f=[fx(**1**),fx(**2**),fx(**3**),fx(**4**),fz(**1**),fz(**2**), fz(**3**),fz(**4**)] are given. Conversely, the fact that the movement vectors can be represented as foregoing means that superposition of forces holds, therefore, the elastic body is a linear elastic body.

When the equation is represented as a matrix form, X=H×f, where H=[Mx(**1**); Mx(**2**); . . . ; Mz(**4**)]. The H is called a transfer function because the H is a map that transfers a force f to deformation x. The matrix form written with an element is the following.

$$\begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix} = \begin{bmatrix} Hmx(1,1) & Hmz(1,1) & Hmx(1,2) & Hmz(1,2) & Hmx(1,3) & Hmz(1,3) & Hnx(1,4) & Hmz(1,4) \\ Hmx(2,1) & Hmz(2,1) & Hmx(2,2) & Hmz(2,2) & Hmx(2,3) & Hmz(2,3) & Hmx(2,4) & Hmz(2,4) \\ Hmx(3,1) & Hmz(3,1) & Hmx(3,2) & Hmz(3,2) & Hmx(3,3) & Hmz(3,3) & Hmx(3,4) & Hmz(3,4) \\ Hmx(4,1) & Hmz(4,1) & Hmx(4,2) & Hmz(4,2) & Hmx(4,3) & Hmz(4,3) & Hmx(4,4) & Hmz(4,4) \\ Hnx(1,1) & Hnz(1,1) & Hnx(1,2) & Hnz(1,2) & Hnx(1,3) & Hnz(1,3) & Hnx(1,4) & Hnz(1,4) \\ Hnx(2,1) & Hnz(2,1) & Hnx(2,2) & Hnz(2,2) & Hnx(2,3) & Hnz(2,3) & Hnx(2,4) & Hnz(2,4) \\ Hnx(3,1) & Hnz(3,1) & Hnx(3,2) & Hnz(3,2) & Hnx(3,3) & Hnz(3,3) & Hnx(3,4) & Hnz(3,4) \\ Hnx(4,1) & Hnz(4,1) & Hnx(4,2) & Hnz(4,2) & Hnx(4,3) & Hnz(4,3) & Hnx(4,4) & Hnz(4,4) \end{bmatrix} \begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix}$$

where Hmx(**x1**, **x2**) represents a displacement amount in x-direction of m marker in a certain depth at a coordinate x=**x1** with a unit force in the x-direction applied to a surface at a coordinate x=**x2**. Similarly; Hnz(**x1**, **x2**) represents a displacement amount in z-direction of n marker in a certain depth at a coordinate x=**x1** with a unit force in the z-direction applied to a surface at a coordinate x=**x2**.

This is a simple multiplication of matrices where reference x is 1×8 matrix reference H is 8×8 square matrix, and reference f comprises 1×8 components. Thus, f can be obtained from observed x by multiplying an inverse matrix of H. Namely, f=inv(H)×X (Equation 1) where inv represents inverse matrix (generalized matrix inverse).

The matrix form written with an element is the following.

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

where Imx(**1**,**1**) and the like represent each element of inv(H) and represent contribution of m(**1**) for calculating fx(**1**).

The important thing is that the number of observed data must be equal to or more than the number of unknowns when determining unknowns by using an inverse matrix defined by a transfer function. To solve this problem, the present invention employs two layers of differentially colored marker groups so as to increase the number of independent observed data up to eight by observing a movement of each marker in the two layered marker groups.

In case of three-dimensional space (where y-axis is added to the drawing), at a point, a force vector has three degrees of freedom, and a horizontal movement vector of markers has two degrees of freedom. If the number of sampling points is four, the number of unknowns f is twelve,

where f=[fx(**1**), fy(**1**), fz(**1**), fx(**2**), fy(**2**), fz(**2**), fx(**3**), fy(**3**), fz(**3**), fx(**4**), fy(**4**), fz(**4**)], whereas the number of observed movement vectors is eight and is insufficient,

where m=[mx(**1**), my(**1**), mx(**2**), my(**2**), mx(**3**), my(**3**), mx(**4**), my(**4**)].

By providing two layered markers, it is possible to obtain sixteen observed data by observing the layered markers and to determine twelve unknowns. Due to redundancy in the number of obtained information, robust extrapolation can be performed. Using the foregoing algorithms, the force vectors are extrapolated from the CCD image. Even with other measurement methods of the present invention using other types of marker configurations, for example, the measurement methods are substantially the same.

[D] Transfer Function Used for Reconstructing Force Vector Distribution

Next, a method of obtaining the transfer function will be described. In an elastic body having a characteristic shape (a semi-infinite elastic body, for example), as a function defining a force applied to a surface and an internal strain, a function where the foregoing equation held in the microscopic region can hold in any regions of the internal portion of the elastic body has been found as a numerical equation. In this case, a matrix H can be obtained by substituting coordinates of finely divided elastic body surfaces and coordinates of internal markers into the function.

Here, the numerical equation is a function G by which the internal strain can be obtained from the surface stress in the form of m(x2, y2)=G(f(x1), x2, y2), where f(x1) represents surface stress and m(x2, y2) represent internal strain. For example, when a force is applied to a point **1** in FIG. **7** and FIG. **8**, displacement of marker **2** can be obtained by m(**2**, y**2**)=G(f(**1**), **2**, y**2**), where y**2** is a known marker depth.

Depending on the shape of elastic body, a matrix H is obtained using the foregoing equation assuming that an elastic body is a semi-infinite elastic body. It is found that surface stress cannot be correctly obtained when the equation for semi-infinite elastic body is applied for an arbitrary curved surface such as a hemispherical surface. It is therefore necessary to associate a surface stress with an internal strain by any other means.

A first method is to associate a surface stress with an internal strain by numerical simulation. By dividing the surface of the sensor into meshes, it is possible to calculate the movement amount of markers when a unit force is applied to each mesh in x-direction, y-direction and z-direction by simulation.

A second method is to actually apply a force to the surface. Forces F**1**, F**2**, F**3**, F**4** . . . , Fn having known magnitude are applied to an arbitrary curved surface of elastic body. Movement vectors (Movements of markers caused by each known force) M**1**, M**2**, M**3**, M**4**, . . . , Mn of markers as to each force applied are measured and stored. F**1** represents three vectors F**1**x, F**1**y, F**1**z and movement vectors of respective markers are given as M**1**x, M**1**y, M**1**z when these forces are applied. A matrix H is obtained from the forces having known magnitude and obtained information (movement vector). The second method will be explained in detail.

Firstly, numerous sampling points are discretely arranged on the surface of elastic body. In one preferable aspect, the sampling points are arranged so as to cover an overall area of the surface. In one aspect, numerous discrete sampling points are arranged (concentrically arranged in plan view) according to curvilinear coordinates. In another aspect, the sampling points are arranged to provide a grid arrangement in a plan view.

At each sampling point, information that associates forces having known magnitude applied in x-direction, y-direction, and z-direction with corresponding movement vectors of markers when the forces are applied is obtained. In one preferable method, forces having the predetermined magnitude are independently applied to each sampling point in x-direction, y-direction and z-direction, and each movement vector of markers is measured and stored. Orientations of x-direction, y-direction and x-direction of force vectors applied on the sampling points are not limited as long as an arbitrary force applied to the surface can be represented by using these force vectors.

Forces applied to each sampling point have known magnitude, and in one preferable aspect, a force with constant magnitude, 100 [gf] for example, is applied to the sampling point in x-direction, y-direction, and z-direction, respectively and movement vectors of each instance are measured. It is not necessary that forces applied to each sampling point have the same magnitude as long as the magnitude of each force is known. Movement vector of markers may be measured based on forces having different magnitudes, and later on, the magnitude of movement vector can be normalized.

As foregoing, the matrix H can be obtained by simulation or measurement where the matrix H is the transfer function that associates force information F with information M as to the behavior of marker (movement information, for example). The optical tactile sensor comprises a memory device and a processor. The matrix H obtained is stored in the memory device. A marker image is obtained by a photographing device when an object contacts the transparent elastic body and an arbitrary force is applied to a surface of a sensor. A movement vector of marker is measured from the obtained marker image by the processor. The measured movement vector of marker is input to the matrix H and calculated by the processor, thereby outputting force vector that is applied to the surface of the elastic body.

[E] Computation Time Reduction Method

Here, if the number of elements of a matrix H becomes large, the time for calculating force distribution from movement information becomes long. This is due to use of movement information for all markers when obtaining force applied to a particular point. In actual fact, in the case of adopting the previously described algorithm, the H matrix becomes gigantic, and time is taken in matrix operation for equation 1. Giving one example, in the case of a mesh of 100×100, there are 10,000 observation points which means that H matrix becomes a gigantic matrix of 10,000×10,000. Generally, in the case of a sensor surface partitioned into N×N, since the number of observation points are N squared, the size of the H matrix becomes N squared by N squared. Thus, time of four times N is taken for matrix operation of equation 1. It means that this problem is brought to the fore for the environment type sensor of the present invention that often comprises a large area surface. Accordingly, it becomes necessary to have a method for shortening the computation time.

The proposed method extracts a part of the H matrix and utilizes the same. As described above, a correspondence relationship for force applied to all lattice points and movement of all markers is described in the H matrix. However, as an actual problem, for example, it is possible to ignore the effect marker provided that a distance between the force application points and the marker is sufficient. If this is done, for example, in FIG. **7** and FIG. **8**, by assuming that it is acceptable to use only first to second markers in calculating f(**1**), and to use only first to third markers in calculating f(**2**), it is possible to make the size of the matrix small. A new matrix in this example is as follows.

Original equation 1 f=inv(H) x is as follows:

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

This equation becomes an equation as follows by ignoring contribution at places separated by distance.

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

Places with zero are points separated by distance that should be ignored. Calculation at higher speed can be effectuated because there is no need to compute them. This speed increase provides an accelerated effect as the lattice size N becomes larger, as described previously.

This is equivalent to using an extracted surface area containing a place where it is desired to obtain force vectors (FIG. **10**). With the situation in the drawing, in a two dimensional image of the entire contact surface, a region in the vicinity of a place where it is desired to obtain force vector distribution is set. Here, in the event that a region in the vicinity of a place where it is desired to obtain force vectors is set, the neighboring region is not necessarily determined based on only a distance in the two dimensional image. Namely, a distance between force application points and a marker is a spatial distance, and in cases such as where marker groups are layered inside an elastic body, there may be cases where it is desirable to consider depth with the marker is provided.

In the case of a contact surface that is an arbitrary curved surface, contribution of places separated by a distance is not always small. Therefore another method of shortening computation time is proposed. First of all, a transfer function (an inverse matrix) is obtained by actual measurement or simulation. A method for producing this type of transfer function has already been described. For example, when looking at elements of a matrix for a transfer function based on actual measurement, if a particular element of the matrix approaches zero, a marker corresponding to the element can be considered to be a marker that can be ignored for the purpose of obtaining a particular force vector. It is possible to compute the force vector with sections where the particular element of the matrix of the transfer function approaches zero automatically omitted from the computation. For example, a threshold representing an index of the extent to which it is possible to ignore in force vector reconstruction is set for the matrix elements, and the value of matrix elements having a value smaller than the threshold value are made zero.

Further, improvement for the computation shortening method will be described. With respect to the point of extracting a particular region of the image, it is the same as for the foregoing computation shortening method. The foregoing method deals with only information inside the extracted region while the improved method provides sampling points outside the extracted region for force to be computed. With respect to movement of the marker, only information inside the extracted region is handled. The sampling points are points for taking into consideration the effect of force from the outside region. That is, movement of a marker inside the extracted region can be affected to a certain extent by force applied outside the extracted region. At the time of reconstructing force vectors based on movement information of markers inside the extracted region, by computing not only force acting inside the extracted region force but also force acting outside the extracted region, force acting inside the extracted region is reconstructed while taken into consideration force acting outside the extracted region.

Also, force sampling points outside the region are set sparsely with distance from the extracted region. This is because it is considered that representation is possible with fewer sampling points because the effect with becomes slighter with increased distance of separation from the region. If description is given based on FIG. **11**, a small region corresponding to sampling points of 5×5 points is set in an image of a tactile sense section. Sampling points are set densely inside the small region. Sampling points for force are also arranged outside the small region. Sampling points for force outside the small region are arranged more sparsely with distance from the small region. With the example in the drawing, at sites close to the small region, sampling points are arranged densely, at the same density as inside the small region, and as separation from the small region increases, the sampling points are arranged more sparsely.

Then, force vectors for sampling points arranged inside and outside the small region are calculated using movement information of markers inside the small region. Of the calculated force vectors, only the results for at least some of the force vectors inside the small region are adopted and saved as final computation results. With the example in FIG. **11**, force vectors for sampling points for force arranged 3×3 inside the small region of 5×5 are saved as final calculation results. Sampling points outside the small region and sampling points not adopted inside the small region are discarded. The extracted small region is then sequentially shifted as obtaining force vectors for the region, so that force vector distribution for the entire measurement region of the sensor is obtained. In FIG. **11**, force vectors for a part of sampling points of the small region are utilized, but it is also possible to utilize force vectors for all sampling points inside the small region. Also, in FIG. **11**, force vectors for a plurality of sampling points for a part of the small region are utilized, but it is also possible to utilize only force vectors for one sampling point inside the small region. In FIG. **11**, a small region of 5×5 points is shown, but the size of the extracted region is not limited. Using this improved method, compared to the above described computation shortening method, the amount of computation may be increased but there is sufficient shortening of the computation time compared to before adopting a speed increasing method.

Description will be given for an improved method, based on FIG. **12** to FIG. **15**. With FIG. **12**, for ease of description of the improved method the number of marker points is increased compared to that shown in FIG. **7** and FIG. **8**. Due to the increased number of marker points, there is a corresponding increase in the number of elements in the equations, and for that reason, in FIG. **13**, only x, z directional movements for a marker n corresponding to force for one particular point is shown. This is equivalent to a situation where only sections corresponding to elements Imx(**1**,**1**), Imx(**2**,**1**), Imx (**3**,**1**), Imx(**4**,**1**), Imx(**1**,**2**), Imx(**2**,**2**), Imx(**3**,**2**) and Imx(**4**,**2**) of matrix inv(H) in equation 3 are extracted and the number of marker points is increased.

The speed increasing method before improvement uses only movement information of markers that exists close to points to which force being obtained is applied, and as shown in FIG. **14**, only movement information for markers m_{10} to m_{14} is used. In this respect, if the speed increasing method after improvement is illustrated, it is as shown in FIG. **15**. That is, not only F_8, but also F_2, F_5, F_9, F_{11} and F_{14} are arranged as force sampling points. In the computed force vectors, only force vectors for F_{X8} and F_{Z8} are utilized.

[F] Other Embodiments of Marker Group

As for a tactile portion of optical tactile sensor, in preferred embodiments, a plurality of groups of markers are embedded in the transparent elastic body, each group of markers being made up of a large number of markers, markers constituting different marker groups having different colors for each group, and the marker groups having a different spatial arrangement. As an example of this differing spatial arrangement, a plurality of marker groups are arranged in a layered manner inside the elastic body. As an example of layered markers, the markers constituting the marker groups are microscopic spherical particles and the spherical markers constituting the marker group for each layer have different colors from each other. As another example of this differing spatial arrangement, a plurality of marker groups are arranged so as to intersect each other. As still another example of this differing spatial arrangement, each marker group is a plane group comprised of a plurality of planes extending in the same direction, and extending directions and colors thereof are different between each marker group. The shape of the colored markers is not particularly limited, and preferable examples can be spherical, cylindrical, columnar, strip shaped or flat.

Though the present invention is described based on the spherical markers as one of preferable aspects, the shape and/or arrangement of markers are not limited to the foregoing. Referring to FIGS. **16** to **19**, other shapes and arrangements of markers will now be described. Detail descriptions of these markers are described in WO02/18893 A1 and incorporated herein by reference. Further, the shape and/or arrangement of markers are not limited to the drawings of the present application and WO02/18893 A1.

Referring to FIG. **16**, colored markers being comprised of extremely thin cylinders or columns having microscopic cross sections are shown. Two marker groups are arranged at different depths from the surface **2**. A marker group made up of extremely thin blue cylindrical markers **40** and another marker group made up of extremely thin red cylindrical markers **30** are embedded along the surface **2** and are layered at different depths from the surface. The markers extend along imaginary lines connecting an object coming into contact with the elastic body and a camera. Arrangement of each marker is not limited to the drawing, and it is possible to provide three or more groups of marker each having different colors.

Referring to an upper view of FIG. **17**, inclined plane markers **300**, **400** are arranged in the elastic body **1** in a step-like fashion. In one preferable aspect, parts (a step-shaped interface) of the elastic body **1** constitute markers **300**, **400**. In another aspect, separate plane markers may be embedded in the elastic body **1**. The interface can be divided into two surface groups, all surfaces in a group having the same direction. The surfaces in each group are made the same color (here one interface **300** is blue, and the other interface **400** is red). It is possible to acquire observation values containing vertical and horizontal components of force vectors at a particular point as information by observation of intensity of the two colors at that point. By sensing the observed intensity, it is possible to reconstruct surface distribution of force vectors.

The surface markers having two colors are illustrated in the upper view of FIG. **17**, but surface markers having three colors may be used. As shown in the lower view of FIG. **17**, using so called pyramid manufacturing where microscopic cubes are gathered at a bottom surface, if three groups of surfaces facing in the same direction are respectively made the same color (for example, red, green and blue), it is possible to respectively obtain degrees of freedom for force acting in a horizontal direction on a contact surface as intensity ratios for three colors, and force acting in a vertical direction using a total intensity of the three colors.

Referring to FIG. **18**, two marker groups (a marker group comprising a plurality of thin red strips arranged in a row and a marker group comprising a plurality of thin blue strips arranged in a row) are aligned so that respective markers are orthogonal to each other, but the spatial arrangement relationship between the plurality of marker groups is not limited. It is also possible for the two sides of the strips constituting the marker to have different colors. In the drawing, side portions of the strip markers extend along an observation direction but the side portions of the strip markers may be inclined to an observation direction.

FIG. **19** shows a sensing part having a plurality of plane markers. The plane markers are normally concealed by concealment markers and each plane marker is partitioned into a plurality of portions having different colors for each portion, and the partitioned portions having the same color constitute each marker group. The plane markers and said concealment markers are provided and spaced with each other in the elastic body, and an arrangement is made such that said the markers are concealed by the concealment markers and not observed in a state where external force is not acting on the transparent elastic body. When shear strain arises, the positions of the concealment markers **6** and the colored markers **20** become offset, giving color. With the sensor in the drawing, the markers are coated with three colors RGB, and it is possible to ascertain the strain direction from the color produced.

INDUSTRIAL APPLICABILITY

The present invention can be widely applied to a tactile sensor. As a preferable example, use of the sensor on a seating surface of a chair enables measurement of the distribution of pressure applied to the hip portion of a person sitting on the chair. Also, use of the sensor on a bed enables measurement of the distribution of pressure caused by a person lying on the bed, and use of a sensor installed on a floor surface enables measurement of walking and gravitational agitation.

The invention claimed is:

1. An optical tactile sensor comprising:
- a tactile section having a transparent elastic body and a plurality of markers provided therein;
- imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body,
- wherein said imaging means comprises a plurality of imaging devices, and each of the plurality of imaging devices is provided such that each of the imaging regions which is captured using each of the respective imaging devices has an overlapped imaging region which partially overlaps; and
- said optical tactile sensor further comprising image integration means for integrating each of the marker images which are obtained using the plurality of imaging devices,
- wherein the image integration means integrates the imaging regions such that identical markers in the overlapped imaging regions are matched, to thereby form an integrated image.

2. The sensor of claim **1**, said sensor comprising a display for displaying an image obtained by each imaging device.

3. The sensor of claim **1** wherein said tactile section comprises a large area tactile section which is formed by combining a plurality of small area tactile sections.

4. The sensor of claim **3** wherein the tactile sensor comprises a unit comprised of one small area tactile section and one imaging means corresponding to the small area tactile section and the tactile sensor is formed by combining a plurality of the units.

5. The sensor of claim **1** wherein said tactile section is comprised of a transparent elastic body and a plurality of groups of markers provided therein, each marker group being made up of a number of colored markers, with markers making up different marker groups having different colors for each group, and the imaging device taking an image of the behavior of colored makers in the transparent elastic body when an object contacts the surface of elastic body.

6. A method of reconstructing force vector using the sensor of claim **5**, said method comprising the steps of:
- obtaining a marker image by taking an image of behavior of colored markers when an object contacts a contact surface of the elastic body;
- obtaining information relating to the marker behavior from the marker image, said information being more than the number of force vectors to be obtained; and
- obtaining force vectors as outputs by inputting said obtained information relating to the marker behavior to a transfer function,
- wherein said obtaining force vectors calculates force vectors omitting information relating to behavior of the marker that has low extent of contribution to force vector calculation.

7. The method of claim **6**, said obtaining force vectors comprising calculating force vectors using only information relating to behavior of markers in the vicinity of a position where it is desired to obtain force vectors.

8. The method of claim **7**, wherein said position comprises one or more sampling points.

9. The method of claim **8**, said method further comprising the steps of:
- arranging a plurality of sampling points around said position;
- obtaining force vectors acting at the sampling points at and around said position using information relating to marker behavior in the vicinity of said position; and
- adopting only force vectors acting at said position in the calculated force vectors.

10. The method of claim **9**, wherein the sampling points are arranged more sparsely as separation from said position.

11. The method of claim **6**, wherein said obtaining force vectors comprising calculating force vectors omitting elements that are close zero in elements of the matrix.

12. A method of reconstructing force vector using the sensor of claim **5**, said method comprising the steps of:
- obtaining a marker image by taking an image of behavior of colored markers when an object contacts a contact surface of the elastic body;
- obtaining information relating to the marker behavior from the marker image, said information being more than the number of force vectors to be obtained;
- setting a small region of a specified size in the marker image and arranging a plurality of force vector sampling points inside and outside the small region;
- calculating force vectors acting on the sampling points by supplying marker information inside the small region to a transfer function; and
- adopting force vectors acting on at least some sampling points of the plurality of sampling points arranged inside the small region.

13. The method of claim **12**, wherein the sampling points are arranged densely inside the small region, and arranged sparsely with distance from the small region.

14. A method for obtaining a marker image using an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and an imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body, said method comprises steps of:
- providing a plurality of imaging devices as the imaging means and obtaining a partial marker image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region; and
- forming an integrated marker image by integrating the partial marker images obtained, using the imaging means such that identical markers in the overlapped photograph regions are matched.

15. The method of claim **14** wherein said tactile portion comprises a transparent elastic body and a plurality of marker groups provided in said body, each marker group is comprised of a number of colored markers, with markers constituting different marker groups having different colors for each group, and said imaging device takes an image of behavior of colored markers when said curved surface of elastic body is contacted by an object.

16. The method of claim **14** wherein calibration of the respective imaging device is conducted using the markers.

17. A method for integrating a marker image, which is employed in an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and a plurality of imaging devices for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body, said image integration method comprising the steps of:

obtaining a partial image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region; and

integrating the partial images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

* * * * *

РОССИЙСКАЯ ФЕДЕРАЦИЯ

(19) **RU** (11) **2 371 686** (13) **C2**

(51) МПК
G01L 5/16 (2006.01)

ФЕДЕРАЛЬНАЯ СЛУЖБА
ПО ИНТЕЛЛЕКТУАЛЬНОЙ СОБСТВЕННОСТИ,
ПАТЕНТАМ И ТОВАРНЫМ ЗНАКАМ

(12) ОПИСАНИЕ ИЗОБРЕТЕНИЯ К ПАТЕНТУ

(21), (22) Заявка: **2006108382/28, 03.03.2005**

(24) Дата начала отсчета срока действия патента:
03.03.2005

(30) Конвенционный приоритет:
16.06.2004 JP 2004-177786

(43) Дата публикации заявки: **27.09.2007**

(45) Опубликовано: **27.10.2009** Бюл. № **30**

(56) Список документов, цитированных в отчете о поиске: **WO 0218893 A1, 07.03.2002. JP 7067020 A, 10.03.1995. JP 2001141660 A, 25.05.2001. SU 1288730 A1, 07.02.1987. RU 10905 U1, 16.08.1999.**

(85) Дата перевода заявки PCT на национальную фазу: **16.03.2006**

(86) Заявка PCT:
JP 2005/003650 (03.03.2005)

(87) Публикация PCT:
WO 2005/124305 (29.12.2005)

Адрес для переписки:
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RU 2371686 C2

RU 2371686 C2

(54) ОПТИЧЕСКИЙ ТАКТИЛЬНЫЙ ДАТЧИК

(57) Реферат:

Настоящее изобретение относится к оптическому тактильному датчику, а именно к тактильному датчику, используемому для получения сил, приложенных к относительно большей площади. Техническим результатом заявленного изобретения является получение информации и формирование целого изображения с помощью маркеров, позволяющего измерять распределение силы на большой площади. Оптический тактильный датчик содержит тактильную часть, содержащую прозрачный гибкий корпус и множество маркеров, расположенных в корпусе, и множество устройств формирования изображения для получения изображения маркера путем фотографирования поведения маркеров, когда объект контактирует с тактильной поверхностью прозрачного гибкого корпуса. Способ использования оптического тактильного датчика содержит этапы получения частичного изображения путем фотографирования частичных областей A, B, C и D прозрачного гибкого корпуса с

(19) KOREAN INTELLECTUAL PROPERTY OFFICE

KOREAN PATENT ABSTRACTS

(11) Publication number: 1020070036015 A

(43) Date of publication of application: 02.04.2007

(21) Application number: 1020067005120

(22) Date of filing: 13.03.2006

(30) Priority: 2004 2004177786 JP 16.06.2004

(51) Int. Cl: *G01L 1/24 (2006.01); G01L 5/16 (2006.01); G06F 3/03 (2006.01); G06F 3/00 (2006.01);*

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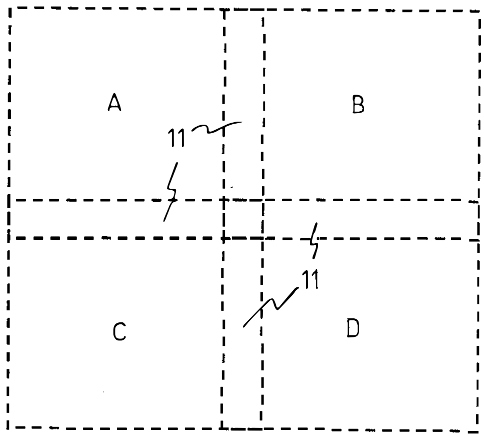
(54) **OPTICAL TACTILE SENSOR**

(57) Abstract:

An optical tactile sensor and an information integrating method capable of measuring large area force vector distribution. The integrating method of a marker image in an optical tactile sensor comprising a tactile section consisting of a transparent resilient body (1) and a plurality of markers (3, 4) provided therein, and a plurality of imaging devices (6, 6) for acquiring a marker image by photographing the behavior of the marker when an object (5) touches the tactile face (2) of the transparent resilient body (1), the method comprising a step for acquiring a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (1) using the plurality of imaging devices (6, 6) such that each imaging device (6) has an overlapped photograph region (11), and a step for integrating the partial images acquired by each imaging device (6) such that the identical markers in the overlapped photograph region match.



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[19] 中华人民共和国国家知识产权局

[51] Int. Cl.
G01L 5/16 (2006.01)
G01L 1/24 (2006.01)

[12] 发明专利申请公开说明书

[21] 申请号 200580000909.6

[43] 公开日 2006 年 10 月 4 日

[11] 公开号 CN 1842701A

[22] 申请日 2005.3.3
[21] 申请号 200580000909.6
[30] 优先权
[32] 2004.6.16 [33] JP [31] 177786/2004
[86] 国际申请 PCT/JP2005/003650 2005.3.3
[87] 国际公布 WO2005/124305 日 2005.12.29
[85] 进入国家阶段日期 2006.3.16
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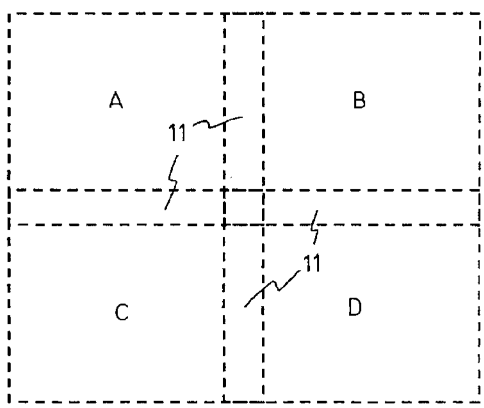
权利要求书 3 页 说明书 17 页 附图 10 页

[54] 发明名称

光学式触觉传感器

[57] 摘要

一种光学式触觉传感器，其能进行大面积力矢量分布测量。提供一种用于能进行大面积力矢量分布测量的信息综合方法。该光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；多个摄影装置，其在物体接触到了该透明弹性体的触觉面时对标志动作进行摄影并取得标志图像。图像综合方法具有：取得部分图像步骤，其通过该多个摄影装置的各摄影装置，使各摄影装置具有重复摄影区域地来摄影该透明弹性体的部分区域 A、B、C、D；综合部分图像步骤，其使该重复摄影区域内的同一标志一致地把由各摄影装置取得的部分图像进行综合。



1、一种光学式触觉传感器，其具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；摄影设备，其在物体接触到该透明弹性体的触觉面时对标志的动作进行摄影并取得标志图像，其特征在于，

该摄影设备由多个摄影装置构成，且该多个摄影装置的各摄影装置被设置成通过各摄影装置取得的各摄影区域具有部分重复的重复摄影区域，

该光学式触觉传感器还具有把由该多个摄影装置取得的各标志图像进行综合的图像综合装置，

该图像综合装置使该重复摄影区域中的同一标志一致地综合各摄影区域，并生成综合图像。

2、如权利要求1所述的光学式触觉传感器，其特征在于，该光学式触觉传感器包含把由各摄影装置取得的图像进行显示的图像显示部。

3、如权利要求1、2任一项所述的光学式触觉传感器，其特征在于，该触觉部是通过组合多个小面积触觉部而构成的大面积触觉部。

4、如权利要求3所述的光学式触觉传感器，其特征在于，其触觉传感器具有由一个小面积触觉部和与该小面积触觉部对应的一个摄影设备构成的单元，并且通过多个该单元进行组合而构成。

5、如权利要求1到4任一项所述的光学式触觉传感器，其特征在于，该触觉部由透明弹性体和设置在该弹性体内的多个标志组构成，各标志组分别由多个有色标志构成，构成不同标志组的标志其每组具有相互不同的颜色，在物体接触了该弹性体的触觉面时通过该摄影设备对该有色标志的动作进行摄影。

6、一种标志信息取得方法，其中，其使用的光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；摄影设备，其在物体接触到该透明弹性体的触觉面时对标志的动作进行摄影并取得标志图像，

该标志图像取得方法，其使用的光学式触觉传感器，且具有：

取得部分标志图像步骤，作为该摄影设备而设置多个摄影装置，该取得部分标志图像步骤通过该多个摄影装置的各摄影装置使各摄影装置具有重复摄影区域地对该透明弹性体的部分区域进行摄影并取得部分标志图

像;

生成综合标志图像步骤，其使该重复摄影区域内的同一标志一致地来综合由各摄影设备取得的部分标志图像并生成综合标志图像。

7、如权利要求6所述的使用了光学式触觉传感器的标志信息取得方法，其特征在于，该触觉部是由透明弹性体和设置在该弹性体内的多个标志组构成，各标志组分别由多个有色标志构成，构成不同标志组的标志其每组具有相互不同的颜色，在物体接触了该弹性体的触觉面时通过摄影设备对该有色标志的动作进行摄影。

8、如权利要求 6、7 任一项所述的使用了光学式触觉传感器的标志信息取得方法，其特征在于，使用该标志进行各摄影装置的校准。

9、一种标志图像综合方法，其中，其使用的光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；多个摄影装置，其在物体接触到该透明弹性体的触觉面时对标志的动作进行摄影并取得标志图像，

该图像综合方法具有：

取得部分图像步骤，其通过该多个摄影装置的各摄影装置使各摄影装置具有重复摄影区域地对该透明弹性体的部分区域进行摄影并取得部分图像;

综合步骤，其使该重复摄影区域内的同一标志一致地综合由各摄影装置取得的部分图像。

10、一种力矢量再构成法，其特征在于，其使用权利要求 5 所述的光学式触觉传感器，该力矢量再构成法包括:

取得标志图像步骤，其在物体接触到了该弹性体的触觉面时对该有色标志的动作进行摄影并取得标志图像;

取得信息步骤，其根据该标志图像取得比要求出的力矢量个数多的关于标志动作的信息;

取得力矢量步骤，其通过把取得的关于标志动作的信息向传递函数输入而把力矢量作为输出来取得，

取得力矢量的步骤在力矢量的计算中省去有关贡献度低的标志动作的信息来计算力矢量。

11、如权利要求10所述的力矢量再构成法，其特征在于，取得力矢量

的步骤，其仅使用有关在要求出的力矢量位置附近的标志动作的信息来计算力矢量。

12、如权利要求 11 所述的力矢量再构成法，其特征在于，该要求出的力矢量位置是由一个或多个采样点所构成。

13、如权利要求 12 所述的力矢量再构成法，其特征在于，其包括:

配置采样点的步骤，其在要求出的该力矢量位置周围配置多个力的采样点;

计算步骤，其使用有关在要求出的力矢量位置附近的标志动作信息来分别计算在该要求出的力矢量位置和该要求出的力矢量位置周围的多个力采样点上起作用的力矢量;

采用步骤，其仅采用在计算出的力矢量中，在该要求出的力矢量位置上起作用的力矢量。

14、如权利要求 13 所述的力矢量再构成法，其特征在于，在该要求出的力矢量位置周围的采样点随着从位于该要求出的力矢量的采样点离开而被稀疏配置。

15、如权利要求 10 所述的力矢量再构成法，其特征在于，取得力矢量步骤在构成该传递函数的矩阵的要素中省略接近于 0 的要素来计算力矢量。

16、一种力矢量再构成法，其特征在于，其使用权利要求 5 所述的光学式触觉传感器，该力矢量再构成法包括:

取得标志图像步骤，其在物体接触到了该弹性体的触觉面时对该有色标志的动作进行摄影并取得标志图像;

取得信息步骤，其根据该标志图像取得比要求出的力矢量个数多的关于标志动作的信息;

配置采样点步骤，其根据该标志图像设定规定大小的小区域，在该小区域内外配置多个力矢量的采样点;

计算力矢量步骤，其把该小区域内的标志信息给予传递函数来计算该多个力矢量在采样点上起作用的力矢量;

采用力矢量步骤，其采用在该小区域内配置的多个采样点的至少一部分采样点上起作用的力矢量。

17、如权利要求 16 所述的力矢量再构成法，其特征在于，采样点在该小区域内被稠密配置，随着从该小区域离开而稀疏配置。

光学式触觉传感器

技术领域

本发明涉及光学式触觉传感器，理想是涉及在比较大的区域内求得力的施加方法所使用的触觉传感器。

背景技术

在考虑通过触觉传感器来了解接触面的接触状态时，加在接触面各点上的力是具有大小和方向的三个分量的矢量。在图 1 的座标系中把它表示为 f(x，y)。其中由于 f 是矢量，所以实际上在各点中具有 x、y、z 这三个分量。在把各自的分量明确进行表示时，则表示为 f（x，y）=[fx（x，y），fy（x，y），fz（x，y）]。由于力分布在各接触点具有三分量，所以，为了通过触觉传感器而把接触面的力分布进行再构成时，至少对于接触面的各点必须得到大于或等于三个的自由度的信息。

本申请的发明者等提案有能测量三维矢量分布的光学式触觉传感器。该光学式触觉传感器的原理可根据图 2 进行说明。光学式触觉传感器是使用透明弹性体 1 和 CCD 照相机的结构。通过把配置在透明弹性体内部的球状标志 3、4 由 CCD 照相机进行摄影，来测量向弹性体表面加力时弹性体内部的变形信息，再构筑力的分布。

把弹性体表面取为 xy 平面，把垂直方向取为 z 轴，通过使用 CCD 照相机从 z 方向对球状标志进行摄影，把加力时测量点的移动作为 xy 平面方向的移动矢量来进行测量。为了根据标志的变形信息来再构筑力矢量分布，在弹性体内部不同的深度把红色球状标志、兰色球状标志作为测量点，通过分别配置 N×N 个，来求出两个深度不同的二维移动矢量，通过把其作为各自不同的信息处理来增加信息量而求出力矢量分布。

作为这种光学式触觉传感器的用途，当初是考虑适用于人型机器人的的机器人手适等，作为光学式触觉传感器的应用是以小型组装型传感器作为中心来研究的。但这种光学式触觉传感器，其在能测量立体力矢量分布的同时，其传感器面是由弹性体构成的，所以不仅是机器人手，还期待其

在各个领域中的应用。

其中之一能举出把光学式触觉传感器作为所谓的环境型触觉传感器使用。本说明书中，对于组装在机器人手等中使用的组装型触觉传感器，把在环境中固定使用的触觉传感器叫做环境型触觉传感器。但在环境中固定使用的环境型触觉传感器中，由于是假想把传感器适用于例如椅子的座面、床铺、地面等，所以考虑需要进行大面积力分布测量，把向机器人手等的组装作为前提的现有的小型光学式触觉传感器不能被原封不动地适用。

专利文献1：国际公开公报WO02/18893A1。

发明内容

本发明的目的在于提供一种能进行大面积力分布测量的光学式触觉传感器。

本发明的其它目的在于提供一种用于能进行大面积力分布测量的标志信息取得方法和标志图像综合方法。本发明的又其它目的在于提供一种能进行大面积力分布测量的光学式触觉传感器中的力矢量再构筑法。

本发明是为了解决该课题而开发的，本光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；摄影设备，其在物体接触到该透明弹性体的触觉面（接触面）时对标志的动作进行摄影并取得标志图像，该摄影设备由多个摄影装置构成，且该多个摄影装置的各摄影装置被设置成通过各摄影装置取得的各摄影区域具有部分重复的重复摄影区域，该光学式触觉传感器还具有把由该多个摄影装置取得的各标志图像进行综合的图像综合装置，该图像综合装置使该重复摄影区域中的同一标志一致地来综合各摄影区域，并生成综合图像。

一个理想的形态是，该触觉部是通过组合多个小面积触觉部而构成的大面积触觉部。且“大面积”、“小面积”的表现是相对的，本说明书中的“大面积”是指比组装在机器人手上的触觉部大的意思，“小面积”是指比“大面积”小的意思。作为“大面积”能举例有椅子的座面、床铺面、地面等，当然比它们小的面积也包含在大面积中。

更理想的是，触觉传感器具有：由一个小面积触觉部和与该小面积触觉部对应的一个摄影设备构成的单元，其通过把该单元组合多个而构成。通过把触觉传感器由传感器单元构成，就能准备具有任意面积的触觉部。

本发明采用的其它技术手段是一种标志图像的取得方法，其使用的光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；摄影设备，其在物体接触到该透明弹性体的触觉面时对标志的动作进行摄影并取得标志图像，该标志图像取得方法，其具有：取得部分标志图像步骤，作为该摄影设备而设置多个摄影装置，该取得标志图像步骤通过该多个摄影装置的各摄影装置使各摄影装置具有重复摄影区域地对该透明弹性体的部分区域进行摄影并取得部分标志图像；生成综合标志图像步骤，其使该重复摄影区域内的同一标志一致地来综合由各摄影设备取得的部分标志图像并生成综合标志图像。

本发明采用的又其它技术手段是一种光学式触觉传感器的标志图像的综合方法，该光学式触觉传感器具有：触觉部，其由透明弹性体和设置在该透明弹性体内的多个标志构成；多个摄影装置，其在物体接触到该透明弹性体的触觉面时对标志的动作进行摄影并取得标志图像，该图像综合方法具有：取得部分图像步骤，其通过该多个摄影装置的各摄影装置使各摄影装置具有重复摄影区域地对该透明弹性体的部分区域进行摄影并取得部分图像；综合步骤，其使该重复摄影区域内的同一标志一致地来综合由各摄影装置取得的部分图像。

作为触觉部的结构，最好该触觉部是由透明弹性体和设置在该弹性体内的多个标志组构成，各标志组分别由多个有色标志构成，构成不同标志组的标志的每组具有相互不同的颜色，在物体接触了该弹性体的触觉面时通过摄影设备对该有色标志的动作进行摄影。

本发明包含使用读出用的标志来进行各摄影设备的校准。本发明具有多个摄影装置，需要进行摄影设备的校准，本发明作为必须结构要素而具有读出用的标志，能把该标志兼用于校准用标志。且本发明还包含使用这种光学式触觉传感器的力矢量再构成法。通过在力矢量的计算中省去有关贡献度低的标志动作的信息来计算力矢量，就缩短了力矢量的计算时间。

本发明由于是使用多个的摄影设备来取得标志有关动作的信息，所以即使在触觉部面积大的情况下也能良好地进行应对。因此，通过使用本发明的传感器就能进行大面积力矢量分布测量，能根据得到的标志信息来求出加在具有大面积的触觉面上的力。且在对各摄影设备取得的图像信息进行综合和各摄影设备的校准中，能利用读出用的标志，能以更少的结构要

素来构成传感器。

附图说明

图 1 是表示在触觉传感器与接触对象之间产生的力矢量分布的图;

图 2 是光学式触觉传感器的原理图，上图是透明弹性体的平面图（CCD 图像），下图是透明弹性体的侧面图，在透明弹性体中埋设了两种标志组，在有力从下方作用在透明弹性体上时，标志从左图向右图地移动;

图 3 是本发明光学式触觉传感器的模式图;

图 4 是说明传感器面大面积化的概略图，左图表示的是由一台 CCD 照相机和弹性体部构成的一个单元，右图表示的是通过铺满一个单元来进行大面积化;

图 5 是表示把由多个摄影设备取得的图像信息进行综合的方法的图;

图 6 是通过图 4 所示传感器取得的图像信息的概略图;

图 7 是说明作用在接触表面（平面）上的力矢量与标志移动的图;

图 8 是说明作用在接触表面（自由曲面）上的力矢量与标志移动的图;

图 9 是在力矢量分布的再构成中使用的传递函数制作法的说明图;

图 10 是由被综合的多台照相机所摄影的图像，是力矢量再构筑计算时间缩短法的说明图，在求加在某点上的力时，仅使用位于其附近区域的标志移动信息来计算力;

图 11 是计算缩短法中改善手法的概念图，图中黑球和白球表示力的采样点，黑球表示计算后利用的计算结果;

图 12 是表示增加标志点数的图;

图 13 是表示增加标志点数的图，是关注对于某一点的力而标志移动的图;

图 14 是根据图 13 来说明图 10 所示高速化手法的图;

图 15 是根据图 13 来说明改善手法的图;

图 16 是表示标志的其它实施例（圆柱状标志）的图;

图 17 是表示标志的其它实施例的图，上图表示是台阶状的带状标志，下图表示是棱锥形状的标志;

图 18 是表示标志的其它实施例（交叉状带片标志）的图;

图 19 是表示标志的其它实施例（被分色的平面标志）的图。

具体实施方式

[A]光学式触觉传感器的基本结构

本发明的光学式触觉传感器具备触觉部和摄影设备，该触觉部由透明弹性体和设置在该弹性体内的多个标志组构成，各标志组分别由多个有色标志构成，构成不同标志组的标志其每组具有相互不同的颜色，在物体接触了该弹性体的触觉面时通过摄影设备对该有色标志的动作进行摄影并取得标志图像，使用从该标志图像得到的关于标志动作的信息来求加在该触觉面上的力。

通过对该有色标志的动作进行摄影，观测在物体接触到了该弹性体时该有色标志的变位、变形、倾斜中的至少一个或一个以上。根据接触对象与传感器接触时的有色标志的信息，能检测透明弹性体内部的变形信息、还有据此计算的接触对象的形状或接触界面（包含弹性体的面、接触对象的面这双方）上作用的力的信息。根据本发明，通过把多种信息进行“分色”的简单方法就能进行个别采集，能通过光学式同时得到多种触觉信息。根据本发明，通过“分色”能收集大于或等于未知数的数量的独立观测值（关于标志的动作的信息），通过稳定地解逆问题，而能推定并再构筑力矢量。

有色标志通过摄影设备，其一个最好的例就是CCD照相机而被摄影，并进行图像处理。例如，标志的动作就能从被摄影的标志图像而作为所求的标志移动信息来取得，把物体接触时与在此以前状态（没有外力作用在透明弹性体上的状态）的图像进行比较，检测标志的移动信息（例如移动矢量）。或在平常时（没有外力作用在透明弹性体上的状态）以不能识认标志的配置状态预先把标志埋设在透明弹性体内，在物体接触到了透明弹性体时，根据由各标志存在位置周边中的变形而引起的标志的变位、变形、倾斜来识认标志，根据有色标志的外观等来检测信息。或者是其它的理想形式是把标志（例如是台阶状的带状标志时）的动作作为标志亮度的变化来取得。

光学式触觉传感器中存储有传递函数，该传递函数用于根据由该摄影设备取得的关于标志动作的信息（例如物体接触到了触觉面时各标志的移动信息，即移动矢量）再构成加在触觉面上的力矢量乃至力矢量分布。传

递函数是与加在触觉面上的力信息和关于标志动作的信息（例如移动矢量）相关联的函数。在物体接触到了弹性体的触觉面时对该有色标志进行摄影并取得标志图像，根据该标志图像取得关于标志动作的信息，通过把取得的信息输入到传递函数中来把力矢量作为输出来求出。向传递函数中输入的关于标志动作的信息的数量比要求出的力矢量的数量多。

传递函数也能由弹性体的形状并根据从弹性体理论导出的式子进行计算，但在弹性体的触觉面是自由曲面的情况下，传递函数最好是通过实测或是模拟来制作。实测或是模拟的传递函数，其是根据在配置于触觉面上的采样点加上 x 方向、y 方向、z 方向规定的力时的关于标志动作的信息（例如移动矢量）来求出的。

图 3 是本发明光学式触觉传感器装置的原理图，传感器装置具有由透光性弹性部件构成的透明弹性体 1，透明弹性体 1 具有曲面状的触觉面（传感器面）2。透明弹性体 1 内接近触觉面 2 处沿触觉面 2 曲面地埋设有多个有色标志 3、4，由透明弹性体 1 和有色标志构成触觉部。

有色标志由两个有色标志组构成，两个标志组分别被埋设在距离触觉面 2 不同的深度处。构成一个标志组的有色标志 3 和构成另一个标志组的有色标志 4 具有相互不同的颜色（例如一方是红色而另一方是兰色）。

当物体 5 接触到透明弹性体 1 的触觉面 2 时，设置在透明弹性体 1 内部的有色标志 3、4 就产生变位或是变形。传感器装置还具备作为摄影设备照相机 6 和光源 7。光学式照相机 6 把透明弹性体 1 夹在中间地被配置在物体 5 接触侧的相反侧（从触觉面 2 离开的一侧）位置上，通过照相机 6 把标志 3、4 的变位、变形进行摄影。光源 7 也可以使用波导管（光纤）进行引导。通过摄影设备即照相机 6 取得的标志 3、4 的图像信息被发送到计算机 8，标志图像被显示在计算机 8 的显示部上，来自标志图像的关于标志动作（变位、变形、倾斜）的标志信息（例如作为移动信息之一的移动矢量）通过计算机 8 的运算部进行测量。在计算机 8 的存储部中存储有所述的传递函数，通过运算部并使用该传递函数和该标志信息（例如移动信息）就能再构筑从物体 5 向触觉面 2 作用的力的分布。

透明弹性体 1 最好是由硅橡胶形成，但也可以由其它橡胶类和弹性材料等其它弹性部件形成。标志最好是由弹性部件形成，更理想的是由与透明弹性体 1 相同的材料构成，作为理想形式之一是在硅橡胶中加有色素的

结构。由于不要由标志给弹性体本体变形带来阻碍，所以使标志也由弹性部件（最好是具有与弹性体同等弹性常数的）形成是理想的。只要标志不阻碍弹性体本体变形的程度是足够微小的，则标志的材质就没有特别的限定。且也可以由弹性体部分来构成标志。

本发明使多个光学标志分布在透明弹性体 1 中，把由物体接触在弹性体 1 上的弹性体 1 的变形而引起的该标志变位、变形、倾斜的状况通过照相机进行摄影，这样来检测接触对象的信息和由接触引起的弹性体内部的变位、变形信息。图 3 是表示了两个标志组，但标志组的数量并不被限定，例如也可以沿触觉面 2 配置三层状的三个标志组。

作为摄影设备的照相机是数字式照相机，即把图像数据作为电信号进行输出的照相机，作为理想例之一的是 CCD 照相机。本发明的摄影设备并不限定于是 CCD 照相机，例如其也可以是使用 C-MOS 式图像传感器的数码照相机。作为标志是准备了红、绿、兰这三种时，为了个别地捕捉它们，有（1）通过摄影器件的滤色片分开（这时只要看照相机的 RGB 输出，就能原封不动地个别摄影各标志）的方法和（2）摄影器件仅捕捉光的强度，作为光源准备红、绿、兰（使红发光时，由于仅具有来自红的标志反射光，而其它两种的标志光被吸收，所以结果是照相机仅捕捉红的标志。若把其利用时间分割即使对绿、兰也进行时，则能得到与（1）等价的信息）的方法这两个。

[B]环境型触觉传感器的结构

说明本发明环境型触觉传感器的实施例。环境型触觉传感器由多个传感器单元构成。如图 4 左图所示，传感器单元由一个小面积触觉部 10 和对小面积触觉部 10 进行摄影的摄影设备，即一个 CCD 照相机所构成。小面积触觉部 10 如在所述基本结构中说明的那样，其由透明弹性体和设置在透明弹性体内部的有色标志构成，在物体接触到透明弹性体的触觉面时，设置在透明弹性体内部的有色标志就移动，把有色标志的移动通过 CCD 照相机 6 进行摄影。如图 4 右图所示，通过组合多个传感器单元来谋求传感器面的大面积化。通过把小面积触觉部 10 相互形成同一个面地使触觉部的端部之间接触铺满来形成大面积触觉部 100。图中所示的是小面积触觉部 10 具有俯视图方形状的形状。小面积触觉部的形状并不限定于方形，但在把多个小面积触觉部铺满时，方形的触觉部是有利的。且图中所示的是具备

平面状触觉面 10 的小面积触觉部，但触觉面 10 并不限定于是平面，其也可以是由自由曲面构成的触觉面。

由于是使用多个 CCD 照相机 6，所以需要把由各个照相机取得的图像信息进行综合。图 5 是对多台照相机图像的综合进行说明的图。该图像例如显示在计算机 8 的显示部上。首先通过多台照相机 6 使各摄影区域相互部分重复地分别取得小面积触觉部 10 的图像。然后使重复摄影区域 11 中的标志相互一致地通过合成各照相机图像来进行图像信息的综合。图 5 中，黑球是兰色标志，白球是红色标志，照相机 1 的摄影区域和照相机 2 的摄影区域具有重复摄影区域 11。为了使照相机 1 的摄影区域中包含在与重复摄影区域 11 对应区域的兰色标志和红色标志、与照相机 2 的摄影区域中包含在与重复摄影区域 11 对应区域的兰色标志和红色标志相一致，而把照相机 1 摄影的部分图像与照相机 2 摄影的部分图像进行合成。在此，是根据球状的标志进行的说明，即使使用后述其它形状的标志，也能同样地进行图像综合。

把图 4 所示四台 CCD 照相机摄影的图像表示在图 6。把由各 CCD 照相机取得的摄影区域分别设定为是 A、B、C、D 时，则区域 A 与区域 B、区域 A 与区域 C、区域 B 与区域 D、区域 C 与区域 D 的各自中形成有重复摄影区域 11 地把各摄影区域 A、B、C、D 进行综合。图 6 中省略了标志。各照相机是对每个照相机预先决定的区域中的标志动作进行摄影，该决定了的区域具有相互重复的区域。作为形式之一，各照相机是预先设定成分别对透明弹性体的规定部分区域进行摄影，通过把由各照相机取得的各规定部分区域的图像进行综合，就能取得透明弹性体整体的图像。

对使用多台摄影设备（CCD 照相机）时的照相机的校准进行说明。照相机校准一般是为了对得到的图像中产生的由透镜引起的失真进行校正和为了求得世界座标系中照相机的位置和方向。透镜的失真是使用广角镜头时所必定发生的，照相机的位置、方向使使用图像信息进行决定最正确。本触觉传感器中就需要求出图像信息与实际位置之间的关系，需要进行照相机校准。通常使用多台照相机的测量系统，其有必要遵循下面的顺序。首先对于世界座标系在已知的位置上配置区分有间隔的条纹图样或白黑的瓦状图样，对其进行摄影。然后使用该摄影图像在没有透镜失真的情况下来计算与应摄影图像的偏差，求出透镜失真和照相机的位置、方向。在此，

在这样相同地使用多台照相机的环境型触觉传感器中，所述的“在已知的位置上区分有间隔的条纹图样和白黑的瓦状图样”是指作为读出用的有色标志已经被配置，作为图像是能取得的状态。因此，本来在组装测量系统之前就必须进行的照相机校准在组装测量系统之后在任何时间都可以进行。

[C]加在触觉面上的力矢量分布再构成法

为了根据由光学式触觉传感器得到的关于标志动作的信息（例如标志的移动信息之一的移动矢量）来求出加在触觉面上的力矢量分布，就需要从关于标志动作的信息（例如移动信息）M 向力信息 F 进行变换。从标志信息 M 向力信息 F 的变换是通过式子 F=HM 来进行的。以下把关于从标志信息再构成力矢量分布的手法，一边参照图 7、图 8 一边根据从标志的移动矢量求力矢量分布的手法进行说明。图 7 和图 8 除了图 7 表示的是平面状触觉面，而图 8 表示的是自由曲面状的触觉面之外，实质上是内容相同。在此为了简单，考虑的是二维断面（没考虑图的 y 轴方向），但在一般的三维情况下，算法也是相同的。

f 是表示作用在接触表面上的力矢量，m、n 分别表示涂有兰、红色标的标志在 CCD 元件上的移动矢量。通过适当的离散化考虑有限的点数（图 7、图 8 中是 4 点）。如前所述，力矢量各自具有三个分量（x、y、z 分量），但在此考虑二个分量（x、z 分量）。在此为了说明上的方便，如图那样仅观测 x 方向的分量。

f=[fx（1），fx（2），fx（3），fx（4），fz（1），fz（2），fz（3），fz（4）]这八个分量是要求出的力分布，

m=[m（1），m（2），m（3），m（4）]，

n=[n（1），n（2），n（3），n（4）]是被观测的移动矢量。把该 m、n 汇总而写成 x。

即 x==[m（1），m（2），m（3），m（4），n（1），n（2），n（3），n（4）]。

在此，把在点 1 上加上 x 方向单位力（大小是 1 的力）时被观测的各标志移动矢量 m、n 进行汇总，写成 Mx（1）。即

Mx（1）=[m（1），m（2），m（3），m（4），n（1），n（2），n（3），n（4）]。

当 f=[1，0，0，0，0，0，0，0]时

同样地，把在点 1 上加上 z 方向单位力时被观测的各标志移动矢量写成 Mz（1），把在点 2 上加上 x 方向单位力时被观测的各标志移动矢量写成 Mx（2）等，以下是同样的决定。在是线性弹性体（在所加的力分布与变位之间线性加法关系成立的弹性体。很多的弹性体满足该性质）的情况下，给予一般的力 f=[fx（1），fx（2），fx（3），fx（4），fz（1），fz（2），fz（3），fz（4）]时所产生的移动矢量 x，其能被如下书写。

X= Mx（1）*fx（1）+Mz（1）*fz（1）+ Mx（2）*fx（2）+…+Mz（4）*fz（4）

把它以矩阵形式书写时，则成为 X=H*f。但 H=[Mx（1）; Mx（2）; … Mz（4）]。该 H 有用于从力 f 向变位 x 传递的映射的意思，所以被叫做传递函数。

按照每个要素书写时，则如下。

[式 1]

$$\begin{bmatrix} m(1)\\ m(2)\\ m(3)\\ m(4)\\ n(1)\\ n(2)\\ n(3)\\ n(4) \end{bmatrix} = \begin{bmatrix} \mathrm{Hmx}(1,1) & \mathrm{Hmz}(1,1) & \mathrm{Hmx}(1,2) & \mathrm{Hmz}(1,2) & \mathrm{Hmx}(1,3) & \mathrm{Hmz}(1,3) & \mathrm{Hmx}(1,4) & \mathrm{Hmz}(1,4)\\ \mathrm{Hmx}(2,1) & \mathrm{Hmz}(2,1) & \mathrm{Hmx}(2,2) & \mathrm{Hmz}(2,2) & \mathrm{Hmx}(2,3) & \mathrm{Hmz}(2,3) & \mathrm{Hmx}(2,4) & \mathrm{Hmz}(2,4)\\ \mathrm{Hmx}(3,1) & \mathrm{Hmz}(3,1) & \mathrm{Hmx}(3,2) & \mathrm{Hmz}(3,2) & \mathrm{Hmx}(3,3) & \mathrm{Hmz}(3,3) & \mathrm{Hmx}(3,4) & \mathrm{Hmz}(3,4)\\ \mathrm{Hmx}(4,1) & \mathrm{Hmz}(4,1) & \mathrm{Hmx}(4,2) & \mathrm{Hmz}(4,2) & \mathrm{Hmx}(4,3) & \mathrm{Hmz}(4,3) & \mathrm{Hmx}(4,4) & \mathrm{Hmz}(4,4)\\ \mathrm{Hnx}(1,1) & \mathrm{Hnz}(1,1) & \mathrm{Hnx}(1,2) & \mathrm{Hnz}(1,2) & \mathrm{Hnx}(1,3) & \mathrm{Hnz}(1,3) & \mathrm{Hnx}(1,4) & \mathrm{Hnz}(1,4)\\ \mathrm{Hnx}(2,1) & \mathrm{Hnz}(2,1) & \mathrm{Hnx}(2,2) & \mathrm{Hnz}(2,2) & \mathrm{Hnx}(2,3) & \mathrm{Hnz}(2,3) & \mathrm{Hnx}(2,4) & \mathrm{Hnz}(2,4)\\ \mathrm{Hnx}(3,1) & \mathrm{Hnz}(3,1) & \mathrm{Hnx}(3,2) & \mathrm{Hnz}(3,2) & \mathrm{Hnx}(3,3) & \mathrm{Hnz}(3,3) & \mathrm{Hnx}(3,4) & \mathrm{Hnz}(3,4)\\ \mathrm{Hnx}(4,1) & \mathrm{Hnz}(4,1) & \mathrm{Hnx}(4,2) & \mathrm{Hnz}(4,2) & \mathrm{Hnx}(4,3) & \mathrm{Hnz}(4,3) & \mathrm{Hnx}(4,4) & \mathrm{Hnz}(4,4) \end{bmatrix} \begin{bmatrix} fx(1)\\ fz(1)\\ fx(2)\\ fz(2)\\ fx(3)\\ fz(3)\\ fx(4)\\ fz(4) \end{bmatrix}$$

其中 Hmx（x1，x2）表示的是由加在座标 x=x2 表面上的 x 方向单位力所引起的座标 x=x1 上在有 m 标志的深度处的 x 方向变位量。同样地，Hnz（x1，x2）表示的是加在座标 x=x2 表面上的 z 方向单位力所引起的座标 x=x1 上在有 n 标志的深度处的 x 方向变位量。

为了从观测到的 x 求 f，只要乘上 H 的逆矩阵便可。即是 f=inv（H）*x（式 1）。但 inv 表示的是逆矩阵（一般来说是一般化逆矩阵）。

按照每个要素书写时，则如式 2。

[式 2]
$$\begin{bmatrix} fx(1)\\ fz(1)\\ fx(2)\\ fz(2)\\ fx(3)\\ fz(3)\\ fx(4)\\ fz(4) \end{bmatrix} = \begin{bmatrix} \mathrm{Imx}(1,1) & \mathrm{Imx}(2,1) & \mathrm{Imx}(3,1) & \mathrm{Imx}(4,1) & \mathrm{Inx}(1,1) & \mathrm{Inx}(2,1) & \mathrm{Inx}(3,1) & \mathrm{Inx}(4,1)\\ \mathrm{Imz}(1,2) & \mathrm{Imz}(2,2) & \mathrm{Imz}(3,2) & \mathrm{Imz}(4,2) & \mathrm{Inz}(1,2) & \mathrm{Inz}(2,2) & \mathrm{Inz}(3,2) & \mathrm{Inz}(4,2)\\ \mathrm{Imx}(1,3) & \mathrm{Imx}(2,3) & \mathrm{Imx}(3,3) & \mathrm{Imx}(4,3) & \mathrm{Inx}(1,3) & \mathrm{Inx}(2,3) & \mathrm{Inx}(3,3) & \mathrm{Inx}(4,3)\\ \mathrm{Imz}(1,4) & \mathrm{Imz}(2,4) & \mathrm{Imz}(3,4) & \mathrm{Imz}(4,4) & \mathrm{Inz}(1,4) & \mathrm{Inz}(2,4) & \mathrm{Inz}(3,4) & \mathrm{Inz}(4,4)\\ \mathrm{Imx}(1,1) & \mathrm{Imx}(2,1) & \mathrm{Imx}(3,1) & \mathrm{Imx}(4,1) & \mathrm{Inx}(1,1) & \mathrm{Inx}(2,1) & \mathrm{Inx}(3,1) & \mathrm{Inx}(4,1)\\ \mathrm{Imz}(1,2) & \mathrm{Imz}(2,2) & \mathrm{Imz}(3,2) & \mathrm{Imz}(4,2) & \mathrm{Inz}(1,2) & \mathrm{Inz}(2,2) & \mathrm{Inz}(3,2) & \mathrm{Inz}(4,2)\\ \mathrm{Imx}(1,3) & \mathrm{Imx}(2,3) & \mathrm{Imx}(3,3) & \mathrm{Imx}(4,3) & \mathrm{Inx}(1,3) & \mathrm{Inx}(2,3) & \mathrm{Inx}(3,3) & \mathrm{Inx}(4,3)\\ \mathrm{Imz}(1,4) & \mathrm{Imz}(2,4) & \mathrm{Imz}(3,4) & \mathrm{Imz}(4,4) & \mathrm{Inz}(1,4) & \mathrm{Inz}(2,4) & \mathrm{Inz}(3,4) & \mathrm{Inz}(4,4) \end{bmatrix} \begin{bmatrix} m(1)\\ m(2)\\ m(3)\\ m(4)\\ n(1)\\ n(2)\\ n(3)\\ n(4) \end{bmatrix}$$

其中 lmx（1，1）等是 inv（H）的各要素，结果是其表示的是用于计算 fx（1）的 m（1）的贡献。

通过使用由传递函数决定的矩阵的逆矩阵来决定未知数的情况下，需要使未知数的个数超过被观测的数据的个数或是相同的个数。为了解决该问题，要准备分色的两层标志组，通过取得两层标志组的各标志的移动，使独立的观测数据的数量增加到八个。

在一般的三维情况下（该图是追加了 y 轴的情况），一点上的力矢量是三个自由度，标志的水平移动矢量是二个自由度。假如采样点同样地是四点时，则未知数是

f=[fx（1），fy（1），fz（1），fx（2），fy（2），fz（2），fx（3），fy（3），fz（3），fx（4），fy（4），fz（4）]存在有 12 个，相对地，被观测的值移动矢量是

m=[mx（1），my（1），mx（2），my（2），mx（3），my（3），mx（4），my（4）]这八个，还是不足。通过把它分为两层来观测，能得到 16 个观测数据，这样，就同定 12 个未知数。使用以上的算法根据 CCD 图像来推定力矢量。即使是使用其它标志的其它测量方法，也仅是观测的数据不同，通过在分色上想办法来收集比未知数的数量多的独立观测值（关于标志动作的信息），而在通过稳定地解逆问题来推定力矢量的点上是相同的。

[D]在力矢量分布的再构成中使用的传递函数

下面说明用于求传递函数（矩阵 H）的手法。在具有某种特征的形的弹性体（例如半无限弹性体）中，作为加在表面上的力与内部变位的函数，利用公式形式发现了把在所述微小区域应满足的关系式能在弹性体内部的所有部位都满足的函数。在这种形的情况下，只要把分割成网格状的弹性体表面（触觉面）的座标和内部标志的座标代入到该函数中，就能求出矩阵 H。

在此，以公式的形式被发现是指把表面应力设定为 fx（1），把内部变位设定为 m（x2，y2）时，以 m（x2，y2）=G（fx（1），x2，y2）的形式发现了从表面应力来求内部变位的函数 G。这时例如在图 7、图 8 中向点 1

加力时，标志 2 的变位则通过 m（x2，y2）=G（fx（1），x2，y2）来求。其中 y2 是标志的深度（已知）。

利用弹性体形状而通过把弹性体形状假定是半无限大弹性体，则使用上述的公式就能取得 H 矩阵。但例如对于半球这样的自由曲面同样地适用半无限大弹性体的公式则是困难的。因此，需要以某种其它的手段使联系表面应力和内部变位相关联。

因此，提案的第一手法是通过数值模拟使表面应力和内部变位相关联的手法。在适用提案的传感器时，首先是把表面分割成网格，利用模拟计算在各网格上加有单位应力（x 方向、y 方向、z 方向）时的标志的移动量。

第二手法是实际上加力。向具有自由曲面的弹性体触觉面上加已知的力 F1、F2、F3、F4、…Fn。测量对于所加各自力的标志的移动矢量 M1、M2、M3、M4、…Mn，并进行保存。F1 是 F1x、F1y、F1z 这三个矢量，在加这些力时各自对应的标志的移动矢量是 M1x、M1y、M1z。使用已知的力和得到的信息（移动矢量）来制作矩阵 H。以下进行具体说明。

在弹性体表面（触觉面）上离散地配置多个采样点。理想的是把采样点配置成覆盖触觉面整个区域。作为形式之一是触觉面上离散的多个采样点的配置是使用极座标进行配置（俯视图是配置成同心状）。其它形式是采样点配置成俯视图网格状。

在各采样点上取得使在 x 方向、y 方向、z 方向上分别作用的已知大小的力与该力作用的各自情况下的标志移动矢量相关联的有关信息。其理想方法之一是在各采样点上分别加 x 方向、y 方向、z 方向规定的力，分别测量该时标志的移动矢量，并进行保存。加在采样点上的力矢量的 x 方向、y 方向、z 方向的取得方法是只要是使用力矢量，并且能表示加在触觉面上的任意的力的，则其方向并不被限定。

加在各采样点上的力是已知的力，其理想形式之一是把规定大小的力，例如 100[gf]分别从 x 方向、y 方向、z 方向加在采样点上，测量各自情况下的标志移动矢量。只要加在各采样点上的力是已知的力，则也可以不一定是相同大小的力，基于不同的已知的力来测量标志移动矢量时，然后，只要把标志移动矢量的大小进行标准化便可。

这样，基于弹性体理论并通过公式、模拟或实测来制作把力信息 F 和关于标志动作的信息（例如移动信息）M 连接起来的传递函数，即矩阵 H。

光学式触觉传感器装置具有存储装置和运算处理装置，预先制作的矩阵 H 被存储在存储装置中。在物体接触在透明弹性体的触觉面上，有任意的力作用在触觉面上的情况下，通过摄影设备来取得标志图像。根据取得的标志图像并利用运算处理装置来测量标志移动矢量。把测量的标志移动矢量输入到矩阵 H 中并通过运算处理装置进行计算，把作用在弹性体触觉面上的力矢量分布进行输出。

[E]计算时间缩短法

在此，当矩阵 H 的要素数大时，则根据移动信息计算力分布的时间就长。这是由在求加在某点上的力时要使用所有的标志移动信息而引起的。实际上在适用所述算法的情况下，H 矩阵是巨大的，（式 1）的矩阵运算耗费时间。举一例来说，在网格是 100×100 的情况下，观测点就是 10000 点，所以 H 矩阵就是 10000×10000 的巨大矩阵。一般来说把传感器面分割成 N×N 时，观测点就是 N 的 2 次幂个，所以 H 矩阵的尺寸就是 N 的 2 次幂×N 的 2 次幂。这样一来，在（式 1）的矩阵运算就需要 N 的 4 次幂时间。这在本发明环境型触觉传感器中（考虑具有大面积触觉部的情况多）表现显著。因此需要用于缩短计算时间的手法。

提案的手法是把 H 矩阵的一部分切出来使用。如上所述，叙述了 H 矩阵的向所有的格子点上加的力与所有的标志移动的对应关系。但作为现实问题是例如所加力的点与标志的距离只要充分离开，就能忽略影响。这样一来，例如在图 7、图 8 中，通过假定在计算 f（1）时则仅使用第 1~2 号标志的移动量、在计算 f（2）时仅使用第 1~3 号标志的移动量便可，而能把矩阵的尺寸缩小。该例的新矩阵如下。

原来的（式 1）f=inv（H）*x 就成为了式 3。

[式 3]

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

该式通过忽略离开了距离之处的贡献而成为了式 4。

[式 4]

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

置 0 的地方是离开了应忽略距离的点。由于该部分不需要计算，所以能更高速地计算。该高速化如前所述，在格子尺寸 N 越大的情况下越能表现加速度上的效果。

这与把包含要求出力矢量部位的某面积切出来使用是等价的（图 10）。图中在触觉面整体的二维图像中设定了要求出的力矢量分布部位的附近区域。在此，设定了要求出的力矢量部位的附近区域的情况下，附近区域也不一定仅根据二维图像中的距离进行判断。即加力的点与标志的距离是空间距离，在标志组是层合在弹性体内的情况下，有时候最好考虑标志设置的深度。

在触觉面是自由曲面的情况下，也不能一概断言离开了距离的部位的贡献就小。于是提出缩短计算时间的其它方法。首先，通过实测或模拟来求传递函数（逆矩阵）。这种传递函数的制作法已经叙述过。例如看根据实测的传递函数矩阵的要素时，只要矩阵的某要素接近 0，则与该要素相乘的标志就能被考虑成是在求某力矢量中也可以被忽略的标志。能把传递函数中矩阵的某要素接近 0 的部分自动地从计算中省略来计算力矢量。例如在力矢量的再构成中对于矩阵要素设定表示能忽略程度的指标的阈值，把具有比该阈值小的值的矩阵要素的值作为 0。

下面说明计算缩短化方法的改善。在把图像的某区域切出来的点上与所述计算时间缩短法是相同的。所述方法中有切出区域，仅对其内部信息进行处理，对此，改善手法是在切出区域外也准备计算的力的采样点。关

于标志的移动最终是仅处理切出区域内的信息。其成为用于考虑来自区域外的力的影响的采样点。即为了考虑切出区域内标志的移动在某种程度上受到加在切出区域外的力的影响，在根据切出区域内标志的移动信息进行力矢量的再构成时，通过不仅计算作用在切出区域内的力，也计算作用在切出区域外的力，一边考虑作用在切出区域外的力，一边再构筑作用在切出区域内的力。

随着区域外力的采样点从切出区域离开，进行稀疏地设定。这是由于考虑到越从区域离开其影响就越轻微，所以也可以使少数采样点来代表的缘故。根据图 11 进行说明时，则是把与 5×5 点的采样点对应的小区域设定在触觉部的图像中。把采样点稠密地配置在小区域内。在小区域外也配置了力的采样点。小区域外的力的采样点是随着从小区域离开而进行稀疏地配置。图中在与小区域邻接的部位是把采样点稠密地配置成与小区域内相同的密度，随着从该小区域离开而把采样点进行稀疏地配置。

使用小区域内标志的移动信息，来计算配置在小区域内外的采样点的力矢量。在计算的力矢量中，仅把位于小区域内的力矢量的至少一部分结果作为最终的计算结果来采用，并进行保存。图 11 中，把 5×5 小区域中的 3×3 的力的采样点中的力矢量作为最终的计算结果保存。小区域外的采样点和小区域内未被采用的采样点的力矢量则被舍弃。通过把切出的小区域顺次错开并取得力矢量，就取得了传感器测量区域整体中的力矢量分布。图 11 中是采用了小区域一部分采样点中的力矢量，但也可以是采用小区域内所有采样点中的力矢量。图 11 中是采用了小区域一部分的多个采样点的力矢量，但也可以是仅采用小区域内一个采样点的力矢量。图 11 表示了 5×5 点的小区域，但切出的小区域的大小并没有限制。根据该改善手法，与所述计算时间缩短法相比，其结果是计算量增加了，但与高速化手法适用前相比则是充分缩短了计算时间。

对于改善手法，根据图 12 到图 15 进行说明。图 12 为了方便进行改善手法的说明，其与图 7、图 8 所示的相比增加了标志点数。通过增加标志点数而使对应的式中的要素数增加了，所以在图 13 中仅记述了标志 n 对于某一点力的 x、z 方向的移动。仅取出了与式 3 中矩阵 inv（H）的要素

Imx（1，1），Imx（2，1），Imx（3，1），Imx（4，1），Imz（1，2），Imz（2，2），Imz（3，2），Imz（4，2）

对应的部分，这与增加标志点数是等价的。

改善前的高速化手法是通过仅使用位于要求出的力所加的点附近的标志移动信息，如图 14 所示那样仅使用 m_{10}~m_{14}的标志移动信息。相对地把改善后的高速化手法在图中进行表现时，则是图 15 那样。即作为力的采样点不仅配置 F8，还配置 F_2，F_5，F_9，F_{11}，F_{14}。在被计算的力矢量中仅采用 F_{x8}、F_{z8}的力矢量。

[F]标志组的其它实施例

光学式触觉传感器的触觉部的理想的形式是在该透明弹性体中埋设多个标志组，各标志组分别由多个标志构成，构成不同标志组的标志其每组具有相互不同的颜色，且该标志组具有相互不同空间的配置。作为该不同空间的配置例能举出：在该弹性体的壁厚内层合状地配置的多个标志组。层合状标志组的具体例是构成该标志组的标志是球状的微细小片，构成各层标志组的球状标志具有相互不同的颜色。其它的空间配置的例能举出：相互交叉配置的多个标志组。作为另一其它的空间配置能举出：各标志组由向相同方向延伸的多个面的组构成，该面的延伸方向和颜色是每个各标志组相互不同。有色标志的形状没有特别的限制，若举合适的例则考虑是球状、圆筒状、圆柱状、带片状、平面状各形状。

本发明根据理想形式之一的球状标志进行了说明，但本发明中使用的标志形状或配置结构并不限定于前面所述。下面根据图 16 到图 19 来说明其它的标志形状和配置结构。关于这些标志的详细情况能参照国际公开公报 WO02/18893A1 中的记载。且标志的形状和配置形式并不限定于是图示的或是所述国际公开公报中所记载的。

图 16 是表示的是由具有微小断面的极细圆筒体或极细圆柱体构成的有色标志。在透明弹性体 1 的厚度内距离触觉面 2 的不同深度中，有垂直状配置多个兰色标志 30 而构成的兰色标志组和垂直状配置多个红色标志 40 而构成的红色标志组分别沿触觉面 2 层合状地配置在距离触觉面 2 的不同深度处。标志沿接触在弹性体上的物体和连接照相机的假想线延伸。各标志的配置形式并不限定于图中所示，且也可以设置相互具有不同颜色的大于或等于三个的标志组。

图 17 上图表示是在弹性体 1 内台阶状配置的倾斜面状的面标志 300、400。最好是弹性体 1 的部分（台阶状的界面）形成标志 300、400，但也可

以把其它体的面标志埋设在弹性体 1 内。台阶状的界面能划分成具有两个相同方向的面组。把各自的组预先着色成相同颜色（一侧的界面 300 是兰色，而另一侧的界面 400 是红色）。通过观测某点上两色的亮度，就能得到把该点中的力矢量的水平、垂直分量作为信息而包含的观测值。通过读出它们就能再构成力矢量的面分布。图 17 上图中表示了两色的带状面标志，但也可以使用具有三色的面标志。如图 17 下图那样使用在底面上集合微细立方体的所谓棱锥结构，只要把向同一方向的三组面组分别着色成同一颜色（例如红、绿、兰），通过三色亮度的比率就能把水平加在接触面上的力的自由度、通过三色的合计亮度就能把垂直加在面上的力分别求出。

图 18 是表示的是在弹性体内把由多个并列设置的红色薄壁带片构成的标志组和由多个并列设置的兰色薄壁带片构成的标志组这两个标志组，相互交叉（图中所示的是正交）地把各自的标志进行配置。多个标志组的空间配置关系并不限定于此。且也可以把构成标志的带片正反面由不同的颜色形成。图中带片标志的面部是沿观测方向延伸的，但该带片标志的面部也可以对于观测方向倾斜状地延伸。

图 19 表示的是具有多个平面标志的触觉部。平面标志平常是通过隐蔽标志被隐蔽的。平面标志被区划成多个部位，各部位被付与相互不同的颜色，各平面标志中具有同色的区分就构成了标志组。该平面标志和该隐蔽标志以相互存在有间隔并设置在该透明弹性体内，在该透明弹性体上没有力作用的状态下，该平面标志被隐蔽而观测不到。是当产生剪切变形时，隐蔽标志和有色标志的位置偏离形成为着色的结构。图中所示圆形标志是从圆的中心分成三等分，分割成三个扇状部，分别被涂成红色、绿色、兰色，能从产生的颜色而知道变形的方向。

本发明能广泛适用于触觉传感器，作为合适的例是利用传感器测量坐在椅子座面上的人臀部上所加的压力分布，利用传感器测量躺在床铺上的人的压力分布，利用传感器测量在地面上的步行和在重心摇动测量等中使用。

图 1

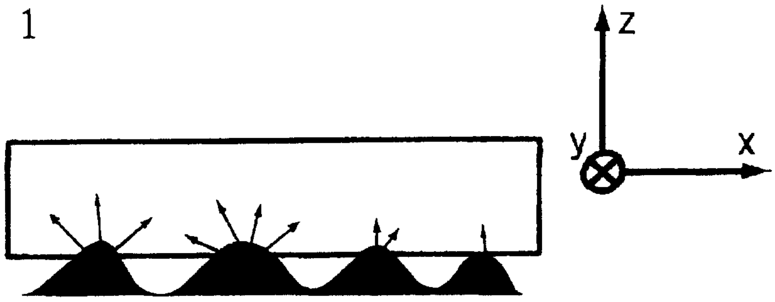


图 2

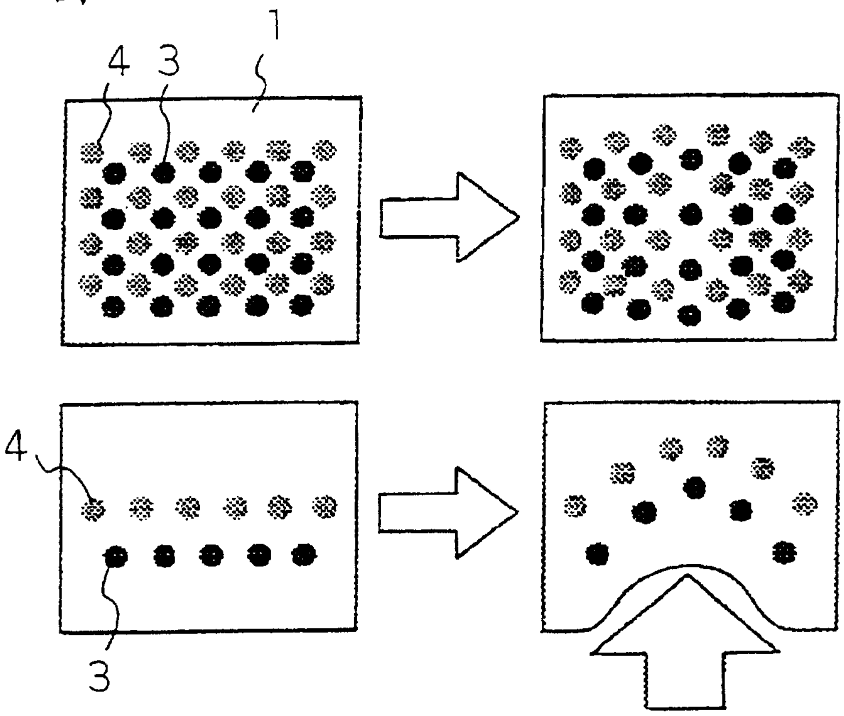


图 3

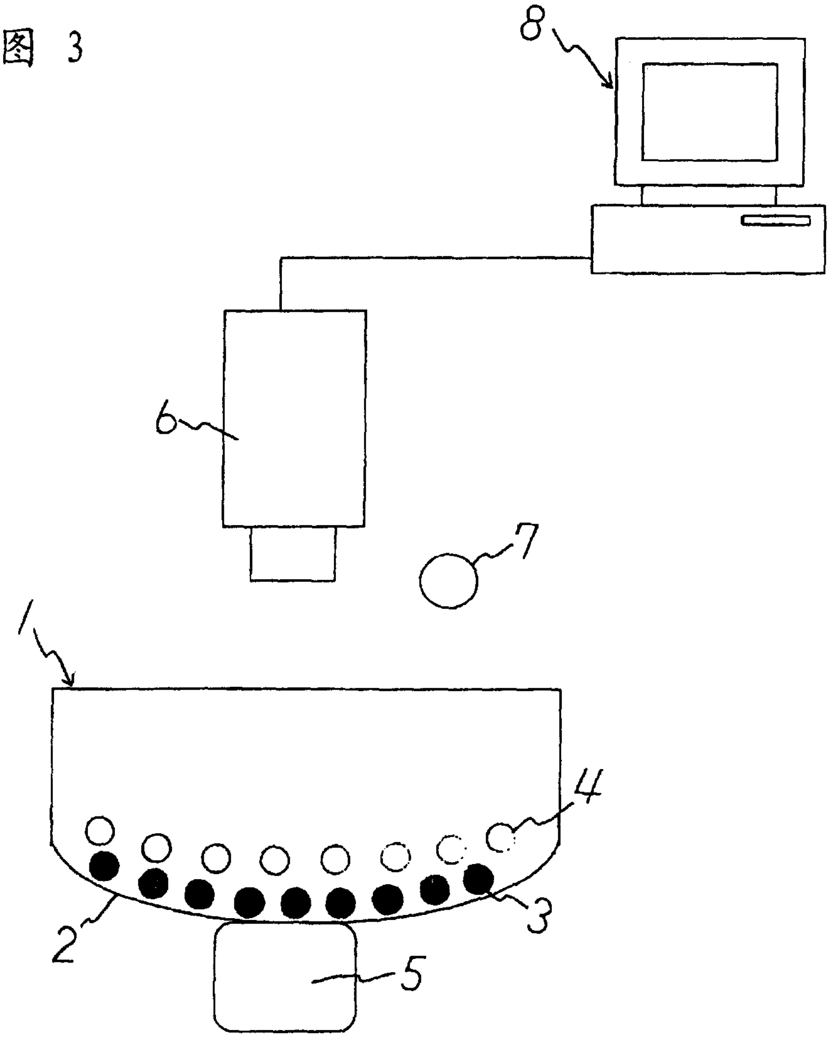
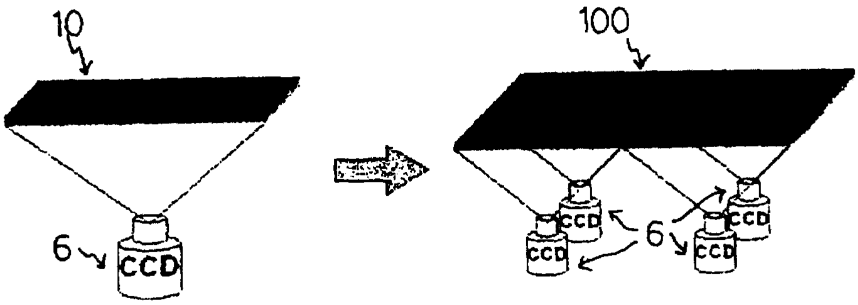


图 4



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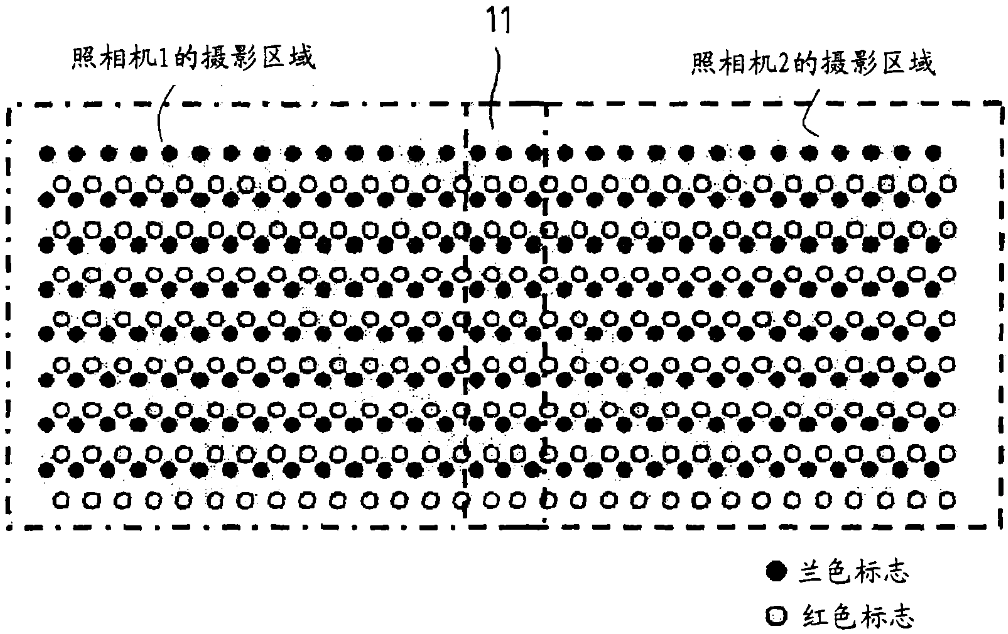

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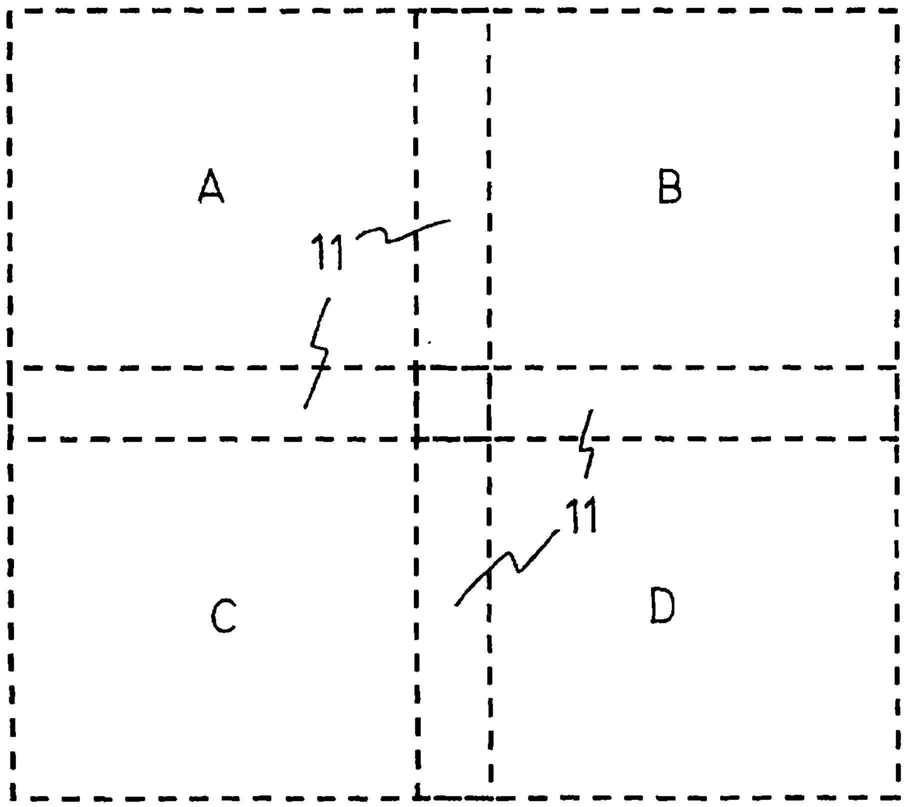


图 7

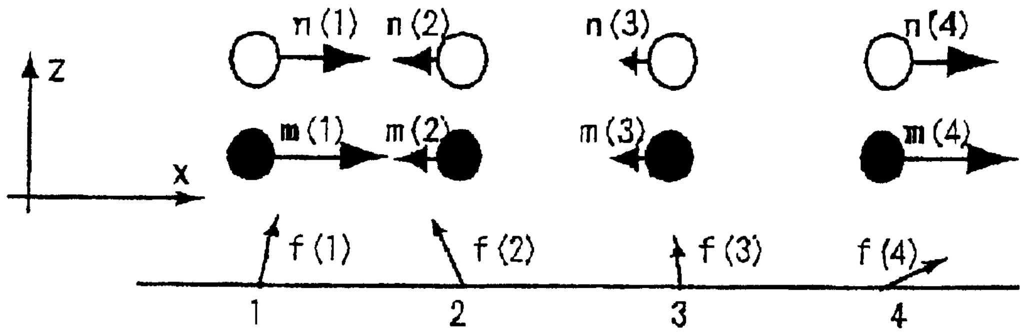

n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
z
x
f(1)
f(2)
f(3)
f(4)
1
2
3
4

图 8

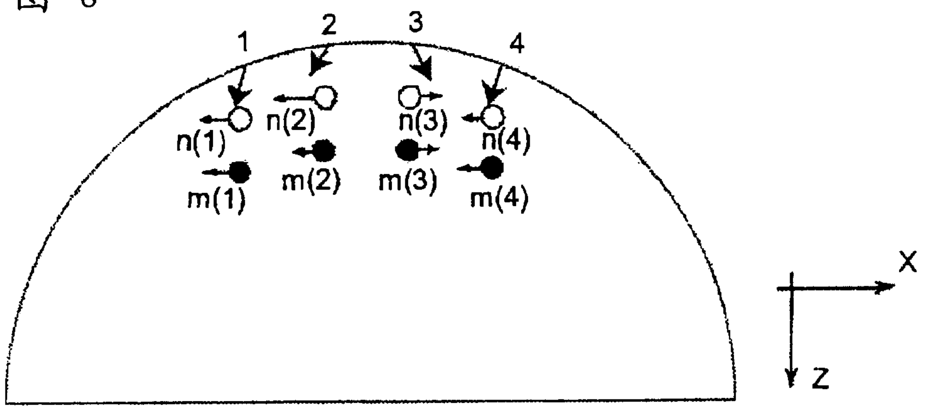

1
2
3
4
n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
X
Z

图 9

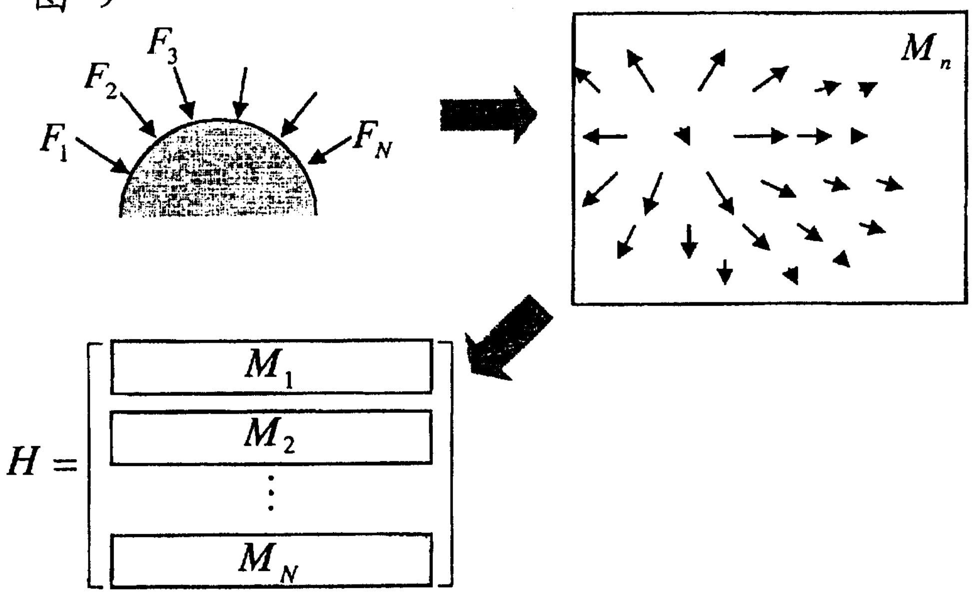

F_1
F_2
F_3
F_N
M_n
$H =$
M_1
M_2
M_N

图 10

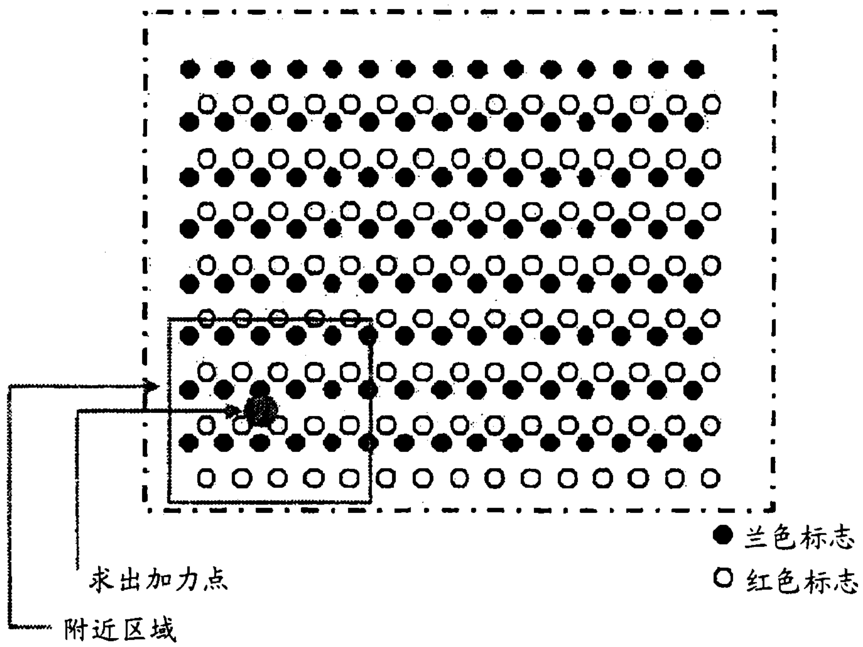
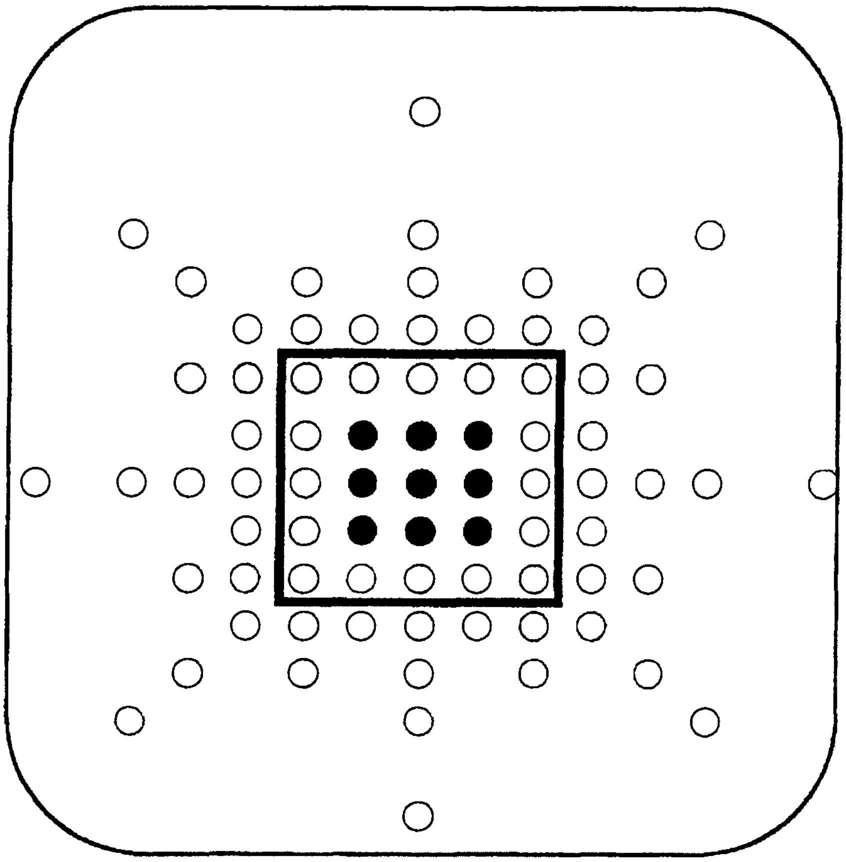


图 11



●○：力的取样点

●：计算后利用的计算结果

图 12

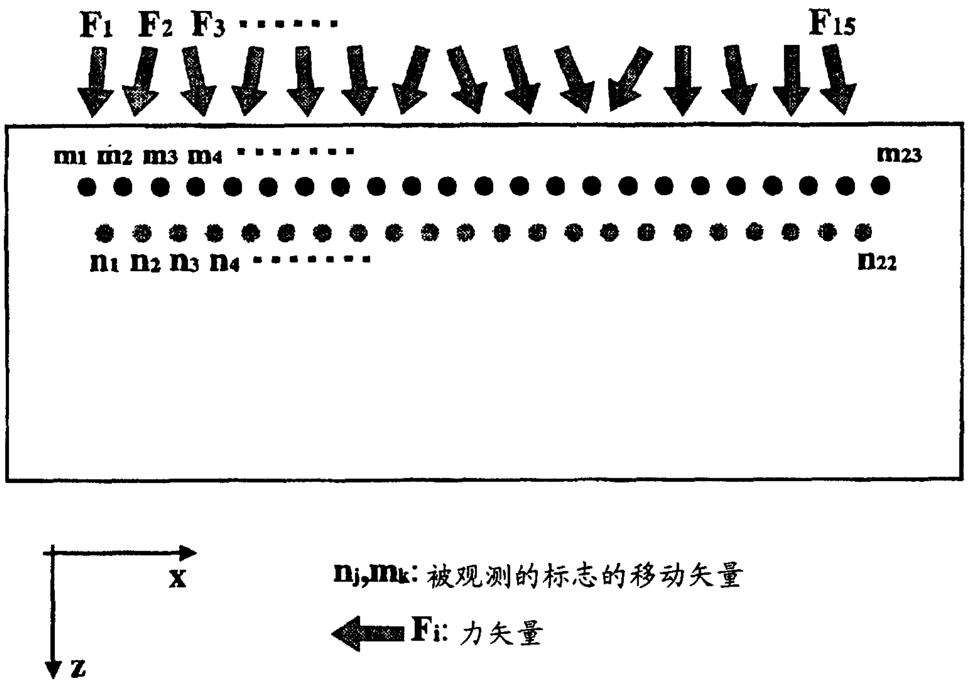

F1 F2 F3 ······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
x
z
nj,mk: 被观测的标志的移动矢量
Fi: 力矢量

图 13

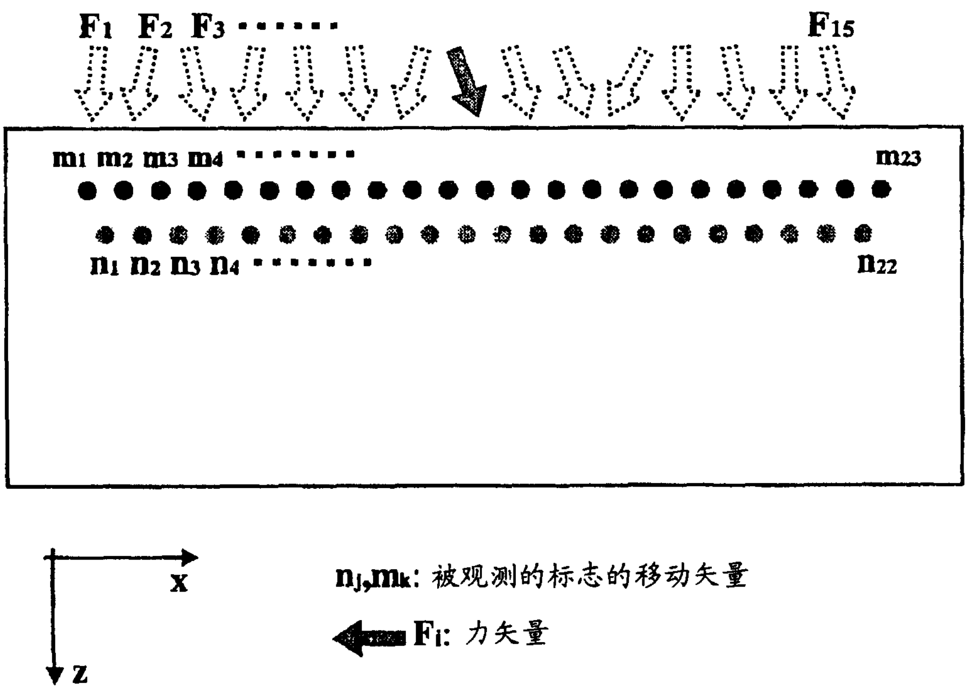
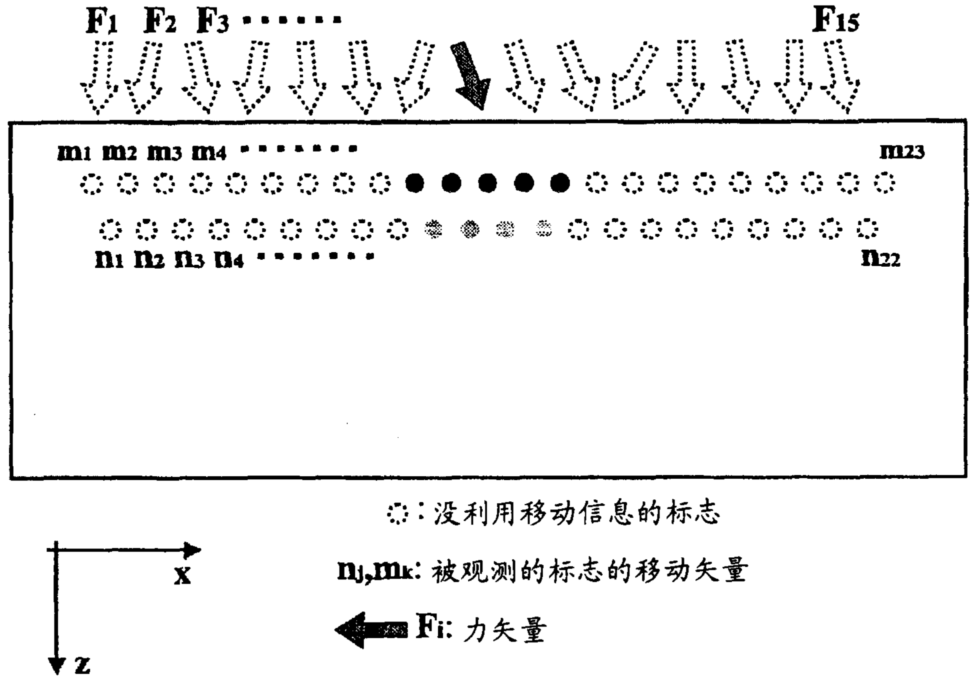
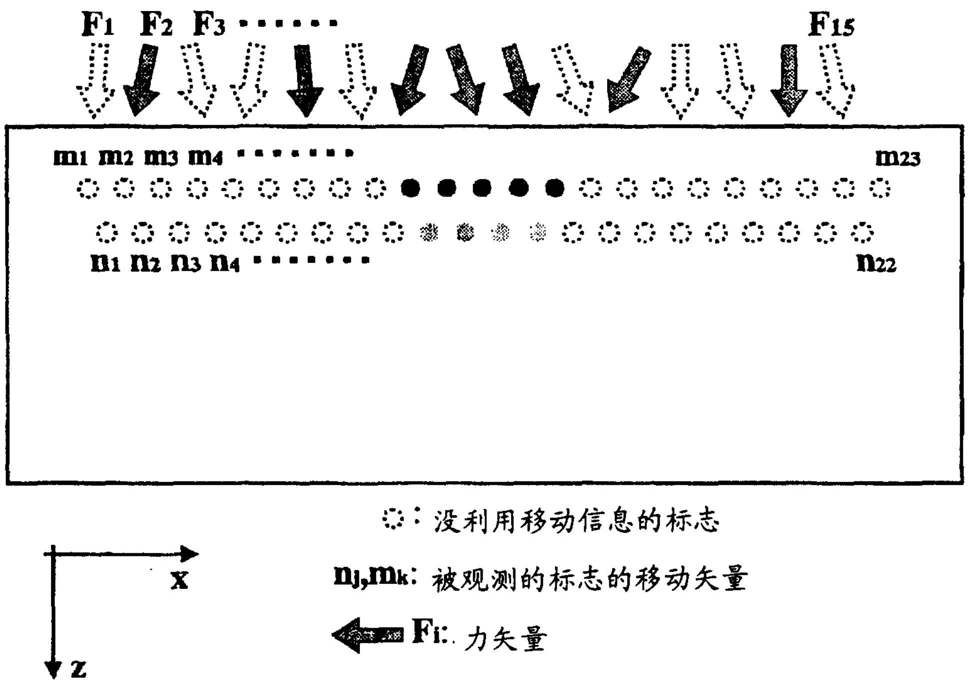

F1 F2 F3 ······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
x
z
nj,mk: 被观测的标志的移动矢量
Fi: 力矢量

图 14



F1 F2 F3 ·······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
：没利用移动信息的标志
x
nj,mk: 被观测的标志的移动矢量
Fi: 力矢量
z

图 15



F1 F2 F3 ·······
F15
m1 m2 m3 m4 ·······
m23
n1 n2 n3 n4 ·······
n22
：没利用移动信息的标志
x
nj,mk: 被观测的标志的移动矢量
Fi: 力矢量
z

图 16

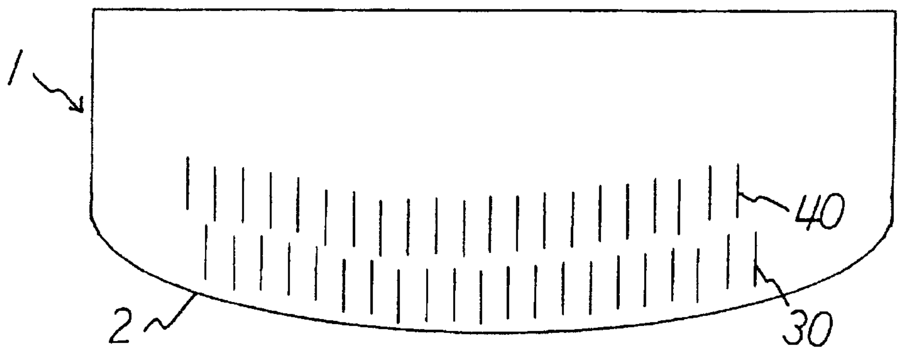
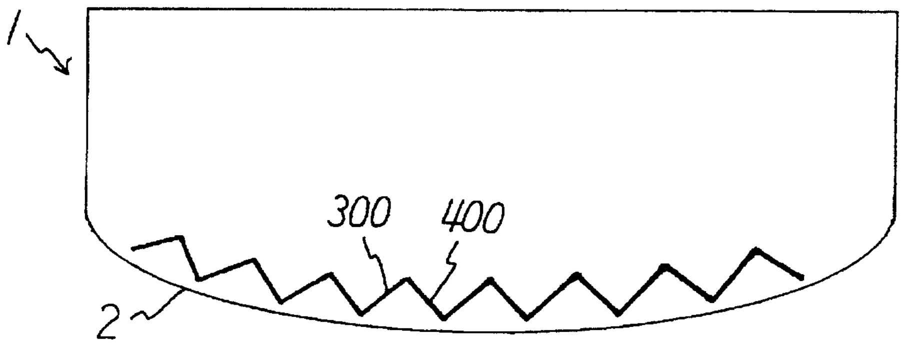


图 17



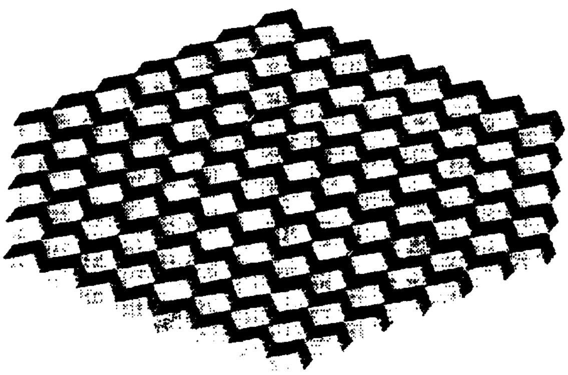


图 18

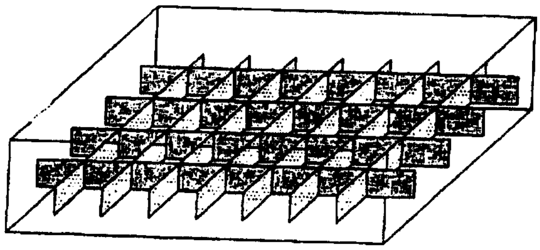
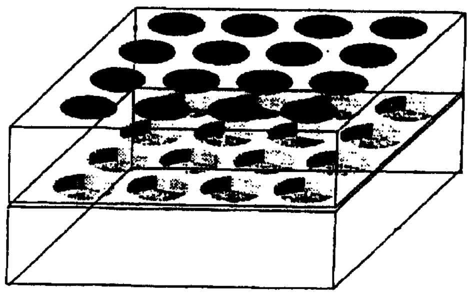


图 19



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SUPPLEMENTARY EUROPEAN SEARCH REPORT

Application Number
EP 05 71 9954

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
	No further relevant documents disclosed -----		INV. G01L5/16 G01L1/24
			TECHNICAL FIELDS SEARCHED (IPC)
			G01L G06F
	The supplementary search report has been based on the last set of claims valid and available at the start of the search.		

1

Place of search	Date of completion of the search	Examiner
The Hague	9 December 2010	Reto, Davide

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(11) **CA 2 538 040** (13) **A1**

(40) **29.12.2005**
(43) **29.12.2005**

(12)

(21) **2 538 040**

(22) **03.03.2005**

(51) Int. Cl.:
G01L 1/24 (2006.01) *G01L 5/16* (2006.01)

(85) **06.03.2006**

(86) **PCT/JP05/003650**

(87) **WO05/124305**

(30) **2004-177786 JP 16.06.2004**

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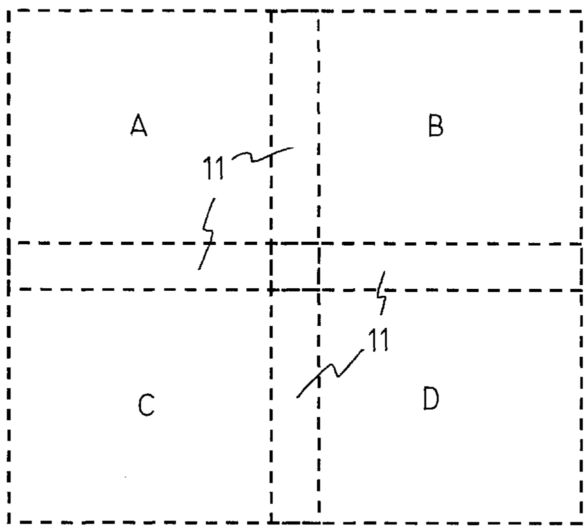
(54) OPTICAL TACTILE SENSOR

(57)
An optical tactile sensor and an information integrating method capable of measuring large area force vector distribution. The integrating method of a marker image in an optical tactile sensor comprising a tactile section consisting of a transparent resilient body (1) and a plurality of markers (3, 4) provided therein, and a plurality of imaging devices (6, 6) for acquiring a marker image by photographing the behavior of the marker when an object (5) touches the tactile face (2) of the transparent resilient body (1), the method comprising a step for acquiring a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (1) using the plurality of imaging devices (6, 6) such that each imaging device (6) has an overlapped photograph region (11), and a step for integrating the partial images acquired by each imaging device (6) such that the identical markers in the overlapped photograph region match.



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CA 2538040 A1 2005/12/29

(21) 2 538 040

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(86) Date de dépôt PCT/PCT Filing Date: 2005/03/03
(87) Date publication PCT/PCT Publication Date: 2005/12/29
(85) Entrée phase nationale/National Entry: 2006/03/06
(86) N° demande PCT/PCT Application No.: JP 2005/003650
(87) N° publication PCT/PCT Publication No.: 2005/124305
(30) Priorité/Priority: 2004/06/16 (JP2004-177786)

(51) Cl.Int./Int.Cl. *G01L 5/16* (2006.01), *G01L 1/24* (2006.01)
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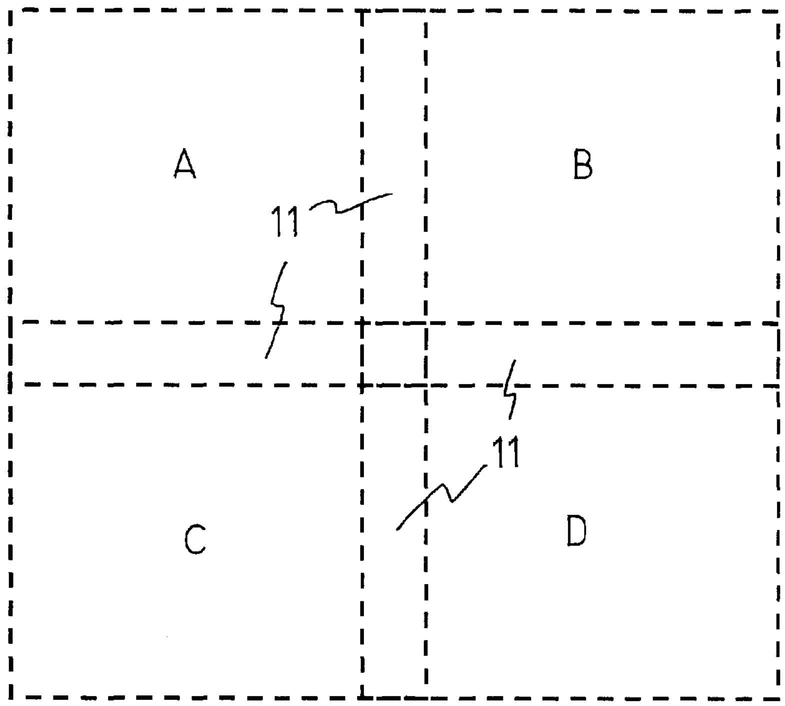
(54) Title: OPTICAL TACTILE SENSOR



(57) Abrégé/Abstract:
An optical tactile sensor and an information integrating method capable of measuring large area force vector distribution. The integrating method of a marker image in an optical tactile sensor comprising a tactile section consisting of a transparent resilient body (1) and a plurality of markers (3, 4) provided therein, and a plurality of imaging devices (6, 6) for acquiring a marker image by photographing the behavior of the marker when an object (5) touches the tactile face (2) of the transparent resilient body (1), the method comprising a step for acquiring a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (1) using the plurality of imaging devices (6, 6) such that each imaging device (6) has an overlapped photograph region (11), and a step for integrating the partial images acquired by each imaging device (6) such that the identical markers in the overlapped photograph region match.

ABSTRACT

An optical tactile sensor and an image information integrating method capable of measuring large area force vector distribution are provided. The optical tactile sensor comprises a tactile section comprising a transparent elastic body (1) and a plurality of markers (3, 4) provided therein, and a plurality of imaging devices (6, 6) for obtaining a marker image by photographing the behavior of the markers when an object (5) contacts the tactile face (2) of the transparent elastic body (1). The method comprises a step of obtaining a partial image by photographing the partial regions A, B, C and D of the transparent resilient body (1) using the plurality of imaging devices (6, 6) such that each imaging device (6) has an overlapped photograph region (11), and a step of integrating the partial images obtained by each imaging device (6) such that the identical markers in the overlapped photograph region match.

SPECIFICATION

OPTICAL TACTILE SENSOR

FIELD OF THE INVENTION

The present invention relates to an optical tactile sensor, and preferably to a tactile sensor used for obtaining forces applied to a relatively larger area.

BACKGROUND OF THE INVENTION

When considering understanding the contact state of a contact surface using a tactile sensor, there are vectors of three components representing magnitude and direction of force acting at each point of the contact surface. This is represented as f(x,y) in the coordinate system of Fig. 1. Here, f is a vector, and so actually has three components x, y and z at each point. When explicitly expressing each component, it is represented as f(x,y) = [fx(x,y), fy(x,y), fz(x,y)]. Since force distribution has three components at each contact point, in order to reconstruct force distribution for each contact surface using a tactile sensor, it is necessary to acquire information for each contact point on the contact surface with at least three degrees of freedom.

Some of inventors of the present invention et al. have proposed an optical tactile sensor that is capable of measuring three-dimensional force vector distribution. A principle of the optical tactile sensor will be explained based on Fig. 2. The optical tactile sensor comprises a transparent elastic body and a CCD camera. By photographing spherical markers embedded in the transparent elastic body by the CCD camera, internal strain information of the elastic body is measured when a force is applied on the surface of the elastic body, and force vector distribution is reconstructed from the information.

By taking an image of the spherical markers by a CCD camera from z-direction where an elastic body surface is taken as the x-y plane and an orthogonal direction to the x-y plane is taken as the z-axis, movement of a point to be measured when force is applied is measured as a movement vector in the x-y plane. To reconstruct the force vector distribution from the strain information, N x N red spherical markers and blue spherical markers are arranged at different depths in the elastic body as points to be measured to obtain two sets of two-dimensional movement vectors with different depths as two pieces of different information, thereby increasing the amount of information to reconstruct the force vector distribution.

As a use for such an optical tactile sensor, initially, application to a robotic hand of a humanoid robot and so forth is considered, and as an application for an optical tactile sensor, study has focused on a small built-in type sensor. However, such an optical tactile sensor, which is capable of measuring three dimensional force vector distribution and has a sensor surface made of a elastic body, is expected to find application in a variety of fields, not only to a robotic hand.

As one of the expected applications, use of an optical tactile sensor as so called an environmental type tactile sensor can be considered. In this specification, as compared to a built-in type tactile sensor which is incorporated for use into a robotic hand or the like, a tactile sensor which is used in a fixed manner in an environment is referred to as an environmental type tactile sensor. However, with respect to an environmental type tactile sensor, which is used in a fixed manner in an environment, measurement of force distribution over a large area is expected to be necessary because such a sensor is assumed to be applied to, for example, a seating surface of a chair, a bed, a floor, or the like. This hinders application of a conventional small optical tactile sensor, which is assumed to be incorporated in a robot hand or the like

Patent Reference: WO02/188923 A1

An object of the present invention is to provide an optical tactile sensor capable of measuring force distribution over a large area.

Another object of the present invention is to provide a marker information acquisition method and a marker image integration method capable of measuring force distribution over a large area. Still another object of the present invention is to provide a force vector reconstruction method employed in an optical tactile sensor capable of measuring force distribution over a large area.

SUMMARY OF INVENTION

The present invention has been conceived in order to solve these problems. According to the present invention, there is provided an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body. The optical tactile sensor is characterized in that the imaging means comprises a plurality of imaging devices, and each of the plurality of imaging devices is provided such that each of the imaging regions which is captured using each of the respective imaging devices has an overlapped imaging region which partially overlaps; the optical tactile sensor further comprising image integration means for integrating each of the marker images which are obtained using the plurality of imaging devices, and the image integration means integrates the imaging regions such that identical markers in the overlapped imaging regions are matched, to thereby form an integrated image.

According to one preferred aspect, the tactile section comprises a large area tactile section which is formed by combining a plurality of small area tactile sections. It should be noted that regarding the relative expressions such as a "large area" and a “small area", in this specification, a "large area" means larger compared to a tactile section such as is to be incorporated into a robotic hand, while a "small area" means smaller compared to a "large area". While a seating surface of a chair, a bed surface, a floor surface, and so forth may be listed as examples of a "large area", objects that are smaller than these items are also included in what is referred to by a "large area".

Further preferably, the tactile sensor comprises a unit comprised of one small area tactile section and one imaging means corresponding to the small area tactile section. The tactile sensor is formed by combining a plurality of the units. Formation of the tactile sensor using sensor units enables creation of a tactile section having a desired area.

The present invention employs another technical means including a method for obtaining a marker image using an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and an imaging means for obtaining a marker image by photographing behavior of a marker when an object contacts the sensing surface of the transparent elastic body. The method of obtaining marker information comprises a step of providing a plurality of imaging devices as the imaging means and obtaining a partial marker image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region, and a step of forming an integrated marker image by integrating the partial marker images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

The present invention employs still another technical means including a method for integrating a marker image, which is employed in an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and a plurality of imaging devices for obtaining a marker image by photographing behavior of a marker when an object contacts the sensing surface of the transparent elastic body. The image integration method comprises a step of obtaining a partial image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region, and a step of integrating the partial images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

As a construction of the tactile portion, preferably, the tactile section comprises a transparent elastic body and a plurality of groups of markers provided inside the elastic body, each marker group being made up of a number of colored markers, with markers making up different marker groups having different colors for each group. The imaging device takes an image of the behavior of colored makers in the transparent elastic body when an object contacts the surface of elastic body.

Also, the present invention includes calibration of each imaging means while using a sensing marker. As the present invention comprises a plurality of imaging devices, calibration of the imaging means is required. As the present invention has a sensing marker as an essential component, the marker can also be used as a calibration marker. Further, the present invention also includes a method for reconstructing a force vector while using such an optical tactile sensor. When a force vector is calculated without the data on the behavior of a marker with less contribution to the force vector calculation, time for force vector calculation can be reduced.

According to the present invention, as the information on the behavior of a marker is obtained using a plurality of imaging means, even a tactile section having a large area can be preferably handled. Therefore, use of a sensor according to the present invention makes it possible to measure force vector distribution over a large area, which in turn makes it possible to determine a force applied to a sensing surface having a large area, based on the obtained marker information. Moreover, as a sensing marker can be used for integration of the image data obtained by the imaging means and calibration of the respective imaging means, the sensor can be formed using a reduced number of components.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a drawing showing force vector distribution exerted between a tactile sensor and an object to be contacted.

Fig. 2 is a drawing showing the principle of an optical tactile sensor. The upper diagram is a plane view (CCD image) of a transparent elastic body, while the lower diagram is a side view of the transparent elastic body. The transparent elastic body has two kinds of marker groups embedded therein. When force is applied to the transparent elastic body from beneath, the marker moves from what is shown in the left diagram to what is shown in the right diagram.

Fig. 3 is a schematic diagram showing an optical tactile sensor according to the present invention.

Fig. 4 is a schematic diagram explaining enlargement of the area of a sensor surface. The left diagram shows one unit comprising one CCD camera and an elastic body section, while the right diagram shows the result of area enlargement combining units.

Fig. 5 is a diagram for showing a method for integrating the image data which is obtained using a plurality of imaging means.

Fig. 6 is a schematic diagram showing image data which is obtained using the sensor shown in Fig. 4.

Fig. 7 is a diagram explaining a force vector applied to a contact surface (plane surface) and movement of the marker.

Fig. 8 is a diagram explaining a force vector applied to a contact surface (free curving surface) and movement of the marker.

Fig. 9 is a diagram explaining a method for creating a transfer function for use in reconstruction of force vector distribution.

Fig. 10 is a diagram showing an integrated image captured using a plurality of cameras and explaining a method for reducing the time for calculation necessary for reconstruction of a force vector, in which, when a force applied to a point is obtained, data on only the markers located in its vicinity are used in the calculate of the force.

Fig. 11 is a conceptual diagram explaining an improved manner of the calculation reduction method. In the drawing, black and whit circles represent sampling points for force, and the black circle shows a result of calculation to be used after the calculation.

Fig. 12 is a diagram showing an increased number of markers.

Fig. 13 is a diagram showing an increased number of markers, in which movement of a marker caused relative to the force applied to one point is focused.

Fig. 14 is a diagram explaining the speed increasing method shown in Fig. 10, based on Fig. 13.

Fig. 15 is a drawing explaining an improved method, based on Fig. 13.

Fig. 16 is a diagram showing another embodiment of a marker (cylindrical marker).

Fig. 17 is a diagram showing another embodiment of a marker. The upper diagram shows a stepwise band marker, while the lower diagram shows a pyramidal marker.

Fig. 18 is a diagram showing another embodiment of a marker (crossing strip marker).

Fig. 19 is a diagram showing another embodiment of a marker (color-discriminated plane marker).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[A] BASIC CONSTRUCTION OF OPTICAL TACTILE SENSOR

An optical tactile sensor of the present invention comprises a sensing section and imaging means. The tactile section comprises a transparent elastic body and a plurality of marker groups provided in said body, each marker group being comprised of a number of colored markers, with markers constituting different marker groups having different colors for each group. The imaging means is provided to take an image of behavior of colored markers when the surface of elastic body is contacted by an object to obtain marker images. A force applied to the surface is reconstructed from information as to the behavior of markers that is obtained from the marker images.

At least one of displacement, strain and inclination of the colored markers when the elastic body contacts an object is observed by photographing behavior of the colored markers. Strain information inside the transparent elastic body is detected from information about the behavior colored markers when a contact object contacts the sensor, and the shape of the contact object calculated from strain information, and information about force acting on a contact interface (including both the elastic body surface and the contact object surface) are also detected. According to the present invention, it is possible to separately collect a plurality of types of information with a simple method called "color coding", and it is possible to acquire a plurality of types of tactile information at the same time with an optical system. According to the present invention, independent observed information (information as to behavior of markers) whose number is equal to or greater than the number of unknowns are collected using color coding, and it is possible to estimate and reconstruct force vectors by stably resolving an inverse problem.

The colored markers are photographed by photographing device, in a preferred example, a CCD camera, and image processing is carried out by a processor. For example, an image at the time of body contact and an image of a previous condition (a condition where external force is not acting on the transparent elastic body) are compared, and an amount of movement of the markers is detected. Alternatively, the markers are embedded in the transparent elastic body in such an arrangement that they can not be recognized normally (in a state where external force is not acting on the transparent elastic body), and a configuration is such that markers are recognized in response to displacement deformation and inclination of markers caused by strain in the vicinity of positions where each of the markers exist when an object contacts the transparent elastic body, and information is detected from the appearance of the colored markers. In another preferable aspect, the behavior of markers (step-like strip markers, for example) can be obtained by variance of marker intensity.

The optical tactile sensor stores a transfer function by which force vectors or force vector distribution applied to the surface of the elastic body are reconstructed from information (movement vectors of each marker when an object contacts the surface, for example) obtained by photographing device as to behavior of markers. The transfer function is a function that associates force information applied to the surface of the sensor with information as to the behavior of markers (movement vectors, for example). The image information of markers is obtained by photographing the colored markers when the object contacts the sensing surface of the elastic body, and the information as to the behavior of markers is obtained from the image information of markers. The force vector is obtained as an output by inputting the obtained information to the transfer function. The number of information as to the behavior of markers that is input to the transfer function is more than the number of force vectors to be obtained.

The transfer function, depending on the shape of the elastic body, may be obtained based on an equation derived from theory of elasticity. However, when the surface of elastic body is an arbitrary curved surface, preferably, the transfer function is obtained by measurement or simulation. The transfer function by measurement or simulation can be obtained from information (movement vectors, for example) as to behavior of markers when x-directional force, y-directional force, and z-directional force having predetermined magnitude, for example, are applied to sampling points arranged on the surface of the sensor.

Referring to Fig. 3, the construction of an optical tactile sensor of the present invention is shown. The sensor comprises a transparent elastic body 1 formed of a transparent elastic material and a curved surface 2, or a surface for sensing. The transparent elastic body 1 is provided with a plurality of colored markers 3, 4 embedded in the transparent elastic body 1 in the vicinity of the surface 2 and along the curved surface 2. A sensing section is comprised of the transparent elastic body 1 and the colored markers 3, 4 arranged inside the elastic body.

The colored markers 3, 4 are comprised of two groups of colored markers and the two marker groups are embedded in different depths respectively from the surface 2. Colored markers 3 constituting one marker group and colored markers 4 constituting the other marker group have different colors to each other. For example, one marker group consists of a plurality of blue markers 3 and the other marker group consists of a plurality of red markers 4.

When an object 5 comes into contact with the transparent elastic body 1, the colored markers 3, 4 provided inside the transparent elastic body 1 are moved due to the internal strain of the elastic body. The sensor is also provided with a camera 6 as a photographing device and a light source 7. The optical camera 6 is arranged at a position on an opposite side to where an object 5 contacts so that the transparent elastic body 1 is provided between the optical camera 6 and the object 5, and behavior or movement of the markers 3, 4 is photographed by the camera 6. The light source 7 may transmit light through a waveguide such as an optical fiber for example. Images of markers 3, 4 obtained by camera 6 as imaging means are transmitted to a computer 8 and the marker images are displayed on a display. The processor of the computer 8 calculates the marker information (movement vectors as movement information, for example) regarding the behavior (displacement, strain or inclination) of markers. The processor reconstructs the distribution of forces applied to the surface 2 by an object 5 using the marker information (movement information, for example) and a transfer function that is stored in the memory device of the computer 8.

The transparent elastic body 1 is preferably made of silicone rubber, but it can also be made from another elastic material such as another type of rubber or elastomer.

The markers are preferably made from an elastic material, and more preferably made from the same material as the transparent elastic body 1. In one preferred embodiment, the colored markers are formed by adding pigment to silicone rubber. Since deformation of the elastic body should not be inhibited by the markers, the markers are also preferably made from an elastic material (preferably having the same elastic constant as the elastic body). The material of the markers is not particularly limited as long as the extent to which deformation of the elastic body is inhibited is sufficiently small. It is also possible for a part of the elastic body to constitute the markers.

With the present invention, a plurality of optical markers are distributed within the transparent elastic body 1, and information about a contacting object and information about displacement and deformation within the elastic body produced by contact are detected by photographing situations where displacement, deformation and inclination arise in the markers due to deformation of the elastic body 1 as a result of the object coming into contact with the elastic body 1 using a camera. Fig. 3 shows two marker groups, but the number of marker group is not limited, and three marker groups may be located in a layered manner along the surface 2.

A camera, as a photographing device, is a digital camera, namely a camera for outputting image data as electrical signals, and in one preferred example is a CCD camera. It is also possible to use, for example, a digital camera using a C-MOS type image sensor. If three types of markers are prepared in red, green and blue, there are two methods of perceiving these three colors individually. The first method is to use color filters for separation where each marker can be regarded as being individually photographed directly by looking at RGB output from the camera. The second method is a method where imaging elements perceive only light intensity and light sources of red green and blue are prepared. When red is shone, light is only reflected from the red markers while the red light is absorbed by the markers of the other two colors, and so the camera effectively only perceives the red markers. If this is also carried out at separate times for green and blue, information equivalent to that using the first method can be acquired.

[B] ENVIRONMENT TYPE TACTILE SENSOR

An embodiment of an environmental type tactile sensor according to the present invention will be described. An environmental type tactile sensor comprises a plurality of sensor units. As shown in the left diagram in Fig. 4, a sensor unit comprises one small area tactile section 10 and one CCD camera 6 which serves as an imaging means for photographing the small area tactile section 10. As described above in connection with a basic structure, the small area tactile section 10 comprises a transparent elastic body and colored markers provided inside the transparent elastic body. When an object contacts the sensing surface of the transparent elastic body, the colored markers provided inside the transparent elastic body move, and the CCD camera 6 photographs the movements of the colored markers. Then, as shown in the right diagram in Fig. 4, a plurality of sensor units are combined to form a sensor surface having a large area. By carpeting the small area tactile sections 10 so as to form the same plane such that the edges of the tactile sections abut to one another, a large area tactile section 100 is formed. The small area tactile section 10 shown has a square shape in a plane view. Although the shape of the small area tactile section is not limited to square, a square tactile section is advantageous when a plurality of small area tactile sections are carpeted. Also, although a small area tactile section having a plane sensing surface 10 is shown in the drawing, the sensing surface 10 is not limited to plane. A sensing surface having an arbitrary curved surface is also applicable.

As a plurality of CCD cameras 6 are used, integration of the image data obtained using the respective cameras 6 is necessary. Fig. 5 is a diagram explaining integration of the images obtained using a plurality of cameras. Such an image is displayed, for example, on a display of a computer 8. Initially, using a plurality of cameras 6, images of the small area tactile section 10 are taken such that the respective photograph regions partially overlap to one another. Thereafter, the respective images from the cameras are integrated such that the markers in the overlapped photograph regions 11 are matched, thus integrating image data. In Fig. 5, a black circle represents a blue marker, while a white circle represents a red marker, and the photograph regions of the camera 1 and the camera 2 have an overlapped photograph region 11. The blue and red markers within a region corresponding to the overlapped photograph region 11 in the photograph region for the camera 1 and those within a region corresponding to the overlapped photograph region 11 in the photograph region for the camera 2 are matched to one another, whereby the partial images captured using the camera 1 and 2 respectively are integrated. It should be noted that although a spherical marker is referred to here, a marker in other shapes such as is described later can be similarly used for image integration.

An image captured using four CCD cameras shown in Fig. 4 is shown in Fig. 6. Supposing that the respective photograph regions photographed by the respective CCD cameras are referred to as A, B, C, and D, the photograph regions A, B, C, and D are integrated such that overlapped photograph regions 11 are resulted in Regions A and B, Regions A and C, Regions B and D, and Regions C and D, respectively. It should be noted that markers are omitted from Fig. 6. Each camera is configured so as to photograph the behavior of the markers located in a region allocated in advance to the camera, and thc respective allocated regions have mutually overlapped regions. According to one aspect, each of the respective cameras is set in advance so as to photograph a predetermined partial region of the transparent elastic body, and configured such that integration of the images of the respective predetermined partial regions obtained using the respective cameras enables formation of the entire image of the transparent elastic body.

Calibration of a camera to be applied when a plurality of imaging means (CCD cameras) are used is described. Generally, camera calibration is applied for correction of distortion caused in the captured image due to the lens and also for determination of the position and orientation of the camera in the world coordination system. Occurrence of distortion due to a lens is inevitable when a wide lens is used. The position and orientation of the camera is most accurately determined when using image data. In this tactile sensor, as correlation between the image data and the actual position needs to be determined, it is necessary to apply camera calibration. Generally, in a measurement system using a plurality of cameras, the following procedure needs to be followed. Initially, a stripe or black-white tile pattern with known pattern intervals is placed in a position which is known relative to the world coordination system, and the pattern is photographed. Then, displacement from an image which would be captured when the lens had no distortion is calculated using the captured image, and the lens distortion and the position and orientation of the camera are determined. Here, in an environmental type tactile sensor which similarly cmploys a plurality of cameras, the stripe or black-white tile pattern with known pattern intervals is already arranged in a known position as a colored marker for sensing and ready to be acquired as an image. Therefore, camera calibration, which originally needs to be conducted before assembly of the measurement system can be conducted anytime after the assemblage.

[C] METHOD OF RECONSTRUCTING FORCE VECTOR DISTRIBUTION ON SENSING SURFACE

To obtain force vector distribution applied to a surface of the sensor from obtained information (movement vectors of markers, for example) as to behavior of markers by an optical tactile sensor, a transformation from information (movement information, for example) M as to the behavior of markers to force information F is required. The transformation from the marker information M to the force information F is obtained by an equation F=HM. Referring to Fig. 7 and Fig. 8, a method of reconstructing the force vector distribution from the marker information will now be described based on a method of obtaining the force vector distribution from the movement vectors of markers. Fig. 7 and Fig. 8 are substantially the same except that Fig. 7 shows a plane sensing surface while Fig. 8 shows an arbitrary curved sensing surface. Here, though, for the purpose of simplification, only two-dimensional section (y-axial direction is omitted) is considered, an algorithm is the same for a general three-dimensional space.

Reference f refers to a force vector applied to a contact surface, and references m and n refer to a movement vector of a blue marker and movement vector of a red marker in the CCD element. Discrete finite points (four points in Fig. 7 and Fig. 8) are considered. As foregoing, force vector distribution has three components (x component, y component and z component), but only two components (x component and z component) are considered. Generally, taking an image by a camera means a projection of a three-dimensional object to a pixel plane of a two-dimensional plane so that marker movements only in the horizontal direction (x component and y component) are projected in the plane. Here, marker movement only in x direction component is observed.

Here, eight components, f=[fx(1), fx(2), fx(3), fx(4), fz(1), fz(2), fz(3), fz(4)] are force vector distribution to be obtained, where m=[m(1), m(2), m(3), m(4)] and n=[n(1), n(2), n(3), n(4)] are movement vectors to be measured. The vectors m and n are represented as X. Namely, X=[m(1), m(2), m(3), m(4), n(1), n(2), n(3), n(4)]. Here, movement vectors m and n that are observed when a unit force (magnitude of 1) in the x-direction is applied to a point 1 are represented as Mx(1).

Namely, Mx(1)=[m(1), m(2), m(3), m(4), n(1), n(2), n(3), n(4)] when f=[1, 0, 0, 0, 0, 0, 0, 0].

Similarly, a movement vector of each marker when a unit force in the z-direction is applied to a point 1 are represented as Mz(1), a movement vector of each marker when a unit force in the x-direction is applied to a point 2 are represented as Mx(2), and so on. In case of a linear elastic body where linear summation relationship holds between applied forces and strains (most elastic bodies meet this characteristics), movement vectors are represented as

X=Mx(1) x fx(1) + Mz(1) x fz(1) + Mx(2) x fx(2)+...+Mz(4) x fz(4),

when general forces f=[fx(1),fx(2),fx(3),fx(4),fz(1),fz(2),fz(3),fz(4)] are given. Conversely, the fact that the movement vectors can be represented as foregoing means that superposition of forces holds, therefore, the elastic body is a linear elastic body.

When the equation is represented as a matrix form, X = H x f, where H=[Mx(1); Mx(2); ...; Mz(4)]. The H is called a transfer function because the H is a map that transfers a force f to deformation x. The matrix form written with an element is the following.

$$\begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix} = \begin{bmatrix} Hmx(1,1) & Hmz(1,1) & Hmx(1,2) & Hmz(1,2) & Hmx(1,3) & Hmz(1,3) & Hmx(1,4) & Hmz(1,4) \\ Hmx(2,1) & Hmz(2,1) & Hmx(2,2) & Hmz(2,2) & Hmx(2,3) & Hmz(2,3) & Hmx(2,4) & Hmz(2,4) \\ Hmx(3,1) & Hmz(3,1) & Hmx(3,2) & Hmz(3,2) & Hmx(3,3) & Hmz(3,3) & Hmx(3,4) & Hmz(3,4) \\ Hmx(4,1) & Hmz(4,1) & Hmx(4,2) & Hmz(4,2) & Hmx(4,3) & Hmz(4,3) & Hmx(4,4) & Hmz(4,4) \\ Hnx(1,1) & Hnz(1,1) & Hnx(1,2) & Hnz(1,2) & Hnx(1,3) & Hnz(1,3) & Hnx(1,4) & Hnz(1,4) \\ Hnx(2,1) & Hnz(2,1) & Hnx(2,2) & Hnz(2,2) & Hnx(2,3) & Hnz(2,3) & Hnx(2,4) & Hnz(2,4) \\ Hnx(3,1) & Hnz(3,1) & Hnx(3,2) & Hnz(3,2) & Hnx(3,3) & Hnz(3,3) & Hnx(3,4) & Hnz(3,4) \\ Hnx(4,1) & Hnz(4,1) & Hnx(4,2) & Hnz(4,2) & Hnx(4,3) & Hnz(4,3) & Hnx(4,4) & Hnz(4,4) \end{bmatrix} \begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix}$$

where Hmx(x1, x2) represents a displacement amount in x-direction of m marker in a certain depth at a coordinate x=x1 with a unit force in the x-direction applied to a surface at a coordinate x=x2. Similarly, Hnz(x1, x2) represents a displacement amount in z-direction of n marker in a certain depth at a coordinate x=x1 with a unit force in the z-direction applied to a surface at a coordinate x=x2.

This is a simple multiplication of matrices where reference x is 1 x 8 matrix reference H is 8x8 square matrix, and reference f comprises 1 x 8 components. Thus, f can be obtained from observed x by multiplying an inverse matrix of H. Namely, f = inv(H) x X Equation 1 where inv represents inverse matrix (generalized matrix inverse).

The matrix form written with an element is the following.

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

where Imx(1,1) and the like represent each element of inv(H) and represent contribution of m(1) for calculating fx(1).

The important thing is that the number of observed data must be equal to or more than the number of unknowns when determining unknowns by using an inverse matrix defined by a transfer function. To solve this problem, the present invention employs two layers of differentially colored marker groups so as to increase the number of independent observed data up to eight by observing a movement of each marker in the two layered marker groups.

In case of three-dimensional space (where y-axis is added to the drawing), at a point, a force vector has three degrees of freedom, and a horizontal movement vector of markers has two degrees of freedom. If the number of sampling points is four, the number of unknowns f is twelve,
where f=[fx(1), fy(1), fz(1), fx(2), fy(2), fz(2), fx(3), fy(3), fz(3), fx(4), fy(4), fz(4)],
whereas the number of observed movement vectors is eight and is insufficient,
where m = [mx(1), my(1), mx(2), my(2), mx(3), my(3), mx(4), my(4)].

By providing two layered markers, it is possible to obtain sixteen observed data by observing the layered markers and to determine twelve unknowns. Due to redundancy in the number of obtained information, robust extrapolation can be performed. Using the foregoing algorithms, the force vectors are extrapolated from the CCD image. Even with other measurement methods of the present invention using other types of marker configurations, for example, the measurement methods are substantially the same.

[D] TRANSFER FUNCTION USED FOR RECONSTRUCTING FORCE VECTOR DISTRIBUTION

Next, a method of obtaining the transfer function will be described. In an elastic body having a characteristic shape (a semi-infinite elastic body, for example), as a function defining a force applied to a surface and an internal strain, a function where the foregoing equation held in the microscopic region can hold in any regions of the internal portion of the elastic body has been found as a numerical equation. In this case, a matrix H can be obtained by substituting coordinates of finely divided elastic body surfaces and coordinates of internal markers into the function.

Here, the numerical equation is a function G by which the internal strain can be obtained from the surface stress in the form of m(x2, y2) = G(f(x1), x2, y2), where f(x1) represents surface stress and m(x2, y2) represent internal strain. For example, when a force is applied to a point 1 in Fig. 7 and Fig. 8, displacement of marker 2 can be obtained by m(2, y2) = G(f(1), 2, y2), where y2 is a known marker depth.

Depending on the shape of elastic body, a matrix H is obtained using the foregoing equation assuming that an elastic body is a semi-infinite elastic body. It is found that surface stress cannot be correctly obtained when the equation for semi-infinite elastic body is applied for an arbitrary curved surface such as a hemispherical surface. It is therefore necessary to associate a surface stress with an internal strain by any other means.

A first method is to associate a surface stress with an internal strain by numerical simulation. By dividing the surface of the sensor into meshes, it is possible to calculate the movement amount of markers when a unit force is applied to each mesh in x-direction, y-direction and z-direction by simulation.

A second method is to actually apply a force to the surface. Forces F1, F2, F3, F4…, Fn having known magnitude are applied to an arbitrary curved surface of elastic body. Movement vectors (Movements of markers caused by each known force) M1, M2, M3, M4, .., Mn of markers as to each force applied are measured and stored. F1 represents three vectors F1x, F1y, F1z and movement vectors of respective markers are given as M1x, M1y, M1z when these forces are applied. A matrix H is obtained from the forces having known magnitude and obtained information (movement vector). The second method will be explained in detail.

Firstly, numerous sampling points are discretely arranged on the surface of elastic body. In one preferable aspect, the sampling points are arranged so as to cover an overall area of the surface. In one aspect, numerous discrete sampling points are arranged (concentrically arranged in plan view) according to curvilinear coordinates. In another aspect, the sampling points are arranged to provide a grid arrangement in a plan view.

At each sampling point, information that associates forces having known magnitude applied in x-direction, y-direction, and z-direction with corresponding movement vectors of markers when the forces are applied is obtained. In one preferable method, forces having the predetermined magnitude are independently applied to each sampling point in x-direction, y-direction and z-direction, and each movement vector of markers is measured and stored. Orientations of x-direction, y-direction and x-direction of force vectors applied on the sampling points are not limited as long as an arbitrary force applied to the surface can be represented by using these force vectors.

Forces applied to each sampling point have known magnitude, and in one preferable aspect, a force with constant magnitude, 100 [gf] for example, is applied to the sampling point in x-direction, y-direction, and z-direction, respectively and movement vectors of each instance are measured. It is not necessary that forces applied to each sampling point have the same magnitude as long as the magnitude of each force is known. Movement vector of markers may be measured based on forces having different magnitudes, and later on, the magnitude of movement vector can be normalized.

As foregoing, the matrix H can be obtained by simulation or measurement where the matrix H is the transfer function that associates force information F with information M as to the behavior of marker (movement information, for example). The optical tactile sensor comprises a memory device and a processor. The matrix H obtained is stored in the memory device. A marker image is obtained by a photographing device when an object contacts the transparent elastic body and an arbitrary force is applied to a surface of a sensor. A movement vector of marker is measured from the obtained marker image by the processor. The measured movement vector of marker is input to the matrix H and calculated by the processor, thereby outputting force vector that is applied to the surface of the elastic body.

[E] COMPUTATION TIME REDUCTION METHOD

Here, if the number of elements of a matrix H becomes large, the time for calculating force distribution from movement information becomes long. This is due to use of movement information for all markers when obtaining force applied to a particular point. In actual fact, in the case of adopting the previously described algorithm, the H matrix becomes gigantic, and time is taken in matrix operation for equation 1. Giving one example, in the case of a mesh of 100 x 100, there are 10,000 observation points which means that H matrix becomes a gigantic matrix of 10,000 x 10,000. Generally, in the case of a sensor surface partitioned into N x N, since the number of observation points are N squared, the size of the H matrix becomes N squared by N squared. Thus, time of four times N is taken for matrix operation of equation 1. It means that this problem is brought to the fore for the environment type sensor of the present invention that often comprises a large area surface. Accordingly, it becomes necessary to have a method for shortening the computation time.

The proposed method extracts a part of the H matrix and utilizes the same. As described above, a correspondence relationship for force applied to all lattice points and movement of all markers is described in the H matrix. However, as an actual problem, for example, it is possible to ignore the effect marker provided that a distance between the force application points and the marker is sufficient. If this is done, for example, in Fig. 7 and Fig. 8, by assuming that it is acceptable to use only first to second markers in calculating f(1), and to use only first to third markers in calculating f(2), it is possible to make the size of the matrix small. A new matrix in this example is as follows.

Original equation 1 f=inv(H) x is as follows:

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & Imx(3,1) & Imx(4,1) & Inx(1,1) & Inx(2,1) & Inx(3,1) & Inx(4,1) \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & Imz(4,2) & Inz(1,2) & Inz(2,2) & Inz(3,2) & Inz(4,2) \\ Imx(1,3) & Imx(2,3) & Imx(3,3) & Imx(4,3) & Inx(1,3) & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ Imz(1,4) & Imz(2,4) & Imz(3,4) & Imz(4,4) & Inz(1,4) & Inz(2,4) & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

This equation becomes an equation as follows by ignoring contribution at places separated by distance.

$$\begin{bmatrix} fx(1) \\ fz(1) \\ fx(2) \\ fz(2) \\ fx(3) \\ fz(3) \\ fx(4) \\ fz(4) \end{bmatrix} = \begin{bmatrix} Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \\ Imx(1,1) & Imx(2,1) & 0 & 0 & Inx(1,1) & Inx(2,1) & 0 & 0 \\ Imz(1,2) & Imz(2,2) & Imz(3,2) & 0 & Inz(1,2) & Inz(2,2) & Inz(3,2) & 0 \\ 0 & Imx(2,3) & Imx(3,3) & Imx(4,3) & 0 & Inx(2,3) & Inx(3,3) & Inx(4,3) \\ 0 & 0 & Imz(3,4) & Imz(4,4) & 0 & 0 & Inz(3,4) & Inz(4,4) \end{bmatrix} \begin{bmatrix} m(1) \\ m(2) \\ m(3) \\ m(4) \\ n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

Places with zero are points separated by distance that should be ignored. Calculation at higher speed can be effectuated because there is no need to compute them. This speed increase provides an accelerated effect as the lattice size N becomes larger, as described previously.

This is equivalent to using an extracted surface area containing a place where it is desired to obtain force vectors (Fig. 10). With the situation in the drawing, in a two dimensional image of the entire contact surface, a region in the vicinity of a place where it is desired to obtain force vector distribution is set. Here, in the event that a region in the vicinity of a place where it is desired to obtain force vectors is set, the neighboring region is not necessarily determined based on only a distance in the two dimensional image. Namely, a distance between force application points and a marker is a spatial distance, and in cases such as where marker groups are layered inside an elastic body, there may be cases where it is desirable to consider depth with the marker is provided.

In the case of a contact surface that is an arbitrary curved surface, contribution of places separated by a distance is not always small. Therefore another method of shortening computation time is proposed. First of all, a transfer function (an inverse matrix) is obtained by actual measurement or simulation. A method for producing this type of transfer function has already been described. For example, when looking at elements of a matrix for a transfer function based on actual measurement, if a particular element of the matrix approaches zero, a marker corresponding to the element can be considered to be a marker that can be ignored for the purpose of obtaining a particular force vector. It is possible to compute the force vector with sections where the particular element of the matrix of the transfer function approaches zero automatically omitted from the computation. For example, a threshold representing an index of the extent to which it is possible to ignore in force vector reconstruction is set for the matrix elements, and the value of matrix elements having a value smaller than the threshold value are made zero.

Further, improvement for the computation shortening method will be described. With respect to the point of extracting a particular region of the image, it is the same as for the foregoing computation shortening method. The foregoing method deals with only information inside the extracted region while the improved method provides sampling points outside the extracted region for force to be computed. With respect to movement of the marker, only information inside the extracted region is handled. The sampling points are points for taking into consideration the effect of force from the outside region. That is, movement of a marker inside the extracted region can be affected to a certain extent by force applied outside the extracted region. At the time of reconstructing force vectors based on movement information of markers inside the extracted region, by computing not only force acting inside the extracted region force but also force acting outside the extracted region, force acting inside the extracted region is reconstructed while taken into consideration force acting outside the extracted region.

Also, force sampling points outside the region are set sparsely with distance from the extracted region. This is because it is considered that representation is possible with fewer sampling points because the effect with becomes slighter with increased distance of separation from the region. If description is given based on Fig. 11, a small region corresponding to sampling points of 5 x 5 points is set in an image of a tactile sense section. Sampling points are set densely inside the small region. Sampling points for force are also arranged outside the small region. Sampling points for force outside the small region are arranged more sparsely with distance from the small region. With the example in the drawing, at sites close to the small region, sampling points are arranged densely, at the same density as inside the small region, and as separation from the small region increases, the sampling points are arranged more sparsely.

Then, force vectors for sampling points arranged inside and outside the small region are calculated using movement information of markers inside the small region. Of the calculated force vectors, only the results for at least some of the force vectors inside the small region are adopted and saved as final computation results. With the example in Fig. 11, force vectors for sampling points for force arranged 3 x 3 inside the small region of 5 x 5 are saved as final calculation results. Sampling points outside the small region and sampling points not adopted inside the small region are discarded.

The extracted small region is then sequentially shifted as obtaining force vectors for the region, so that force vector distribution for the entire measurement region of the sensor is obtained. In Fig. 11, force vectors for a part of sampling points of the small region are utilized, but it is also possible to utilize force vectors for all sampling points inside the small region. Also, in Fig. 11, force vectors for a plurality of sampling points for a part of the small region are utilized, but it is also possible to utilize only force vectors for one sampling point inside the small region. In Fig. 11, a small region of 5 x 5 points is shown, but the size of the extracted region is not limited. Using this improved method, compared to the above described computation shortening method, the amount of computation may be increased but there is sufficient shortening of the computation time compared to before adopting a speed increasing method.

Description will be given for an improved method, based on Fig. 12 to Fig. 15. With Fig. 12, for ease of description of the improved method the number of marker points is increased compared to that shown in Fig. 7 and Fig. 8. Due to the increased number of marker points, there is a corresponding increasc in the number of elements in the equations, and for that reason, in Fig. 13, only x, z directional movements for a marker n corresponding to force for one particular point is shown. This is equivalent to a situation where only sections corresponding to elements Imx(1,1), Imx(2,1), Imx(3,1), Imx(4,1), Imx(1,2), Imx(2,2), Imx(3,2) and Imx(4,2) of matrix inv(H)in equation 3 are extracted and the number of marker points is increased.

The speed increasing method before improvement uses only movement information of markers that exists close to points to which force being obtained is applied, and as shown in Fig. 14, only movement information for markers m_{10} to m_{14} is used. In this respect, if the speed increasing method after improvement is illustrated, it is as shown in Fig. 15. That is, not only F_8, but also F_2, F_5, F_9, F_{11} and F_{14} are arranged as force sampling points. In the computed force vectors, only force vectors for F_{X8} and F_{Z8} are utilized.

[F] OTHER EMBODIMENTS OF MARKER GROUP

As for a tactile portion of optical tactile sensor, in preferred embodiments, a plurality of groups of markers are embedded in the transparent elastic body, each group of markers being made up of a large number of markers, markers constituting different marker groups having different colors for each group, and the marker groups having a different spatial arrangement. As an example of this differing spatial arrangement, a plurality of marker groups are arranged in a layered manner inside the elastic body. As an example of layered markers, the markers constituting the marker groups are microscopic spherical particles and the spherical markers constituting the marker group for each layer have different colors from each other. As another example of this differing spatial arrangement, a plurality of marker groups are arranged so as to intersect each other. As still another example of this differing spatial arrangement, each marker group is a plane group comprised of a plurality of planes extending in the same direction, and extending directions and colors thereof are different between each marker group. The shape of the colored markers is not particularly limited, and preferable examples can be spherical, cylindrical, columnar, strip shaped or flat.

Though the present invention is described based on the spherical markers as one of preferable aspects, the shape and/or arrangement of markers are not limited to the foregoing. Referring to Figs 16 to 19, other shapes and arrangements of markers will now be described. Detail descriptions of these markers are described in WO02/18893 A1 and incorporated herein by reference. Further, the shape and/or arrangement of markers are not limited to the drawings of the present application and WO02/18893 A1.

Referring to Fig. 16, colored markers being comprised of extremely thin cylinders or columns having microscopic cross sections are shown. Two marker groups are arranged at different depths from the surface 2. A marker group made up of extremely thin blue cylindrical markers 40 and another marker group made up of extremely thin red cylindrical markers 30 are embedded along the surface 2 and are layered at different depths from the surface. The markers extend along imaginary lines connecting an object coming into contact with the elastic body and a camera. Arrangement of each marker is not limited to the drawing, and it is possible to provide three or more groups of marker each having different colors.

Referring to an upper view of Fig. 17, inclined plane markers 300, 400 are arranged in the elastic body 1 in a step-like fashion. In one preferable aspect, parts (a step-shaped interface) of the elastic body 1 constitute markers 300, 400. In another aspect, separate plane markers may be embedded in the elastic body 1. The interface can be divided into two surface groups, all surfaces in a group having the same direction. The surfaces in each group are made the same color (here one interface 300 is blue, and the other interface 400 is red). It is possible to acquire observation values containing vertical and horizontal components of force vectors at a particular point as information by observation of intensity of the two colors at that point. By sensing the observed intensity, it is possible to reconstruct surface distribution of force vectors.

The surface markers having two colors are illustrated in the upper view of Fig. 17, but surface markers having three colors may be used. As shown in the lower view of Fig. 17, using so called pyramid manufacturing where microscopic cubes are gathered at a bottom surface, if three groups of surfaces facing in the same direction are respectively made the same color (for example, red, green and blue), it is possible to respectively obtain degrees of freedom for force acting in a horizontal direction on a contact surface as intensity ratios for three colors, and force acting in a vertical direction using a total intensity of the three colors.

Referring to Fig.18, two marker groups (a marker group comprising a plurality of thin red strips arranged in a row and a marker group comprising a plurality of thin blue strips arranged in a row) are aligned so that respective markers are orthogonal to each other, but the spatial arrangement relationship between the plurality of marker groups is not limited. It is also possible for the two sides of the strips constituting the marker to have different colors. In the drawing, side portions of the strip markers extend along an observation direction but the side portions of the strip markers may be inclined to an observation direction.

Fig. 19 shows a sensing part having a plurality of plane markers. The plane markers are normally concealed by concealment markers and each plane marker is partitioned into a plurality of portions having different colors for each portion, and the partitioned portions having the same color constitute each marker group. The plane markers and said concealment markers are provided and spaced with each other in the elastic body, and an arrangement is made such that said the markers are concealed by the concealment markers and not observed in a state where external force is not acting on the transparent elastic body. When shear strain arises, the positions of the concealment markers 6 and the colored markers 20 become offset, giving color. With the sensor in the drawing, the markers are coated with three colors RGB, and it is possible to ascertain the strain direction from the color produced.

INDUSTRIAL APPLICABILITY

The present invention can be widely applied to a tactile sensor. As a preferable example, use of the sensor on a seating surface of a chair enables measurement of the distribution of pressure applied to the hip portion of a person sitting on the chair. Also, use of the sensor on a bed enables measurement of the distribution of pressure caused by a person lying on the bed, and use of a sensor installed on a floor surface enables measurement of walking and gravitational agitation.

CLAIMS

1. An optical tactile sensor comprising:

a tactile section having a transparent elastic body and a plurality of markers provided therein;

imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body,

wherein said imaging means comprises a plurality of imaging devices, and each of the plurality of imaging devices is provided such that each of the imaging regions which is captured using each of the respective imaging devices has an overlapped imaging region which partially overlaps; and

said optical tactile sensor further comprising image integration means for integrating each of the marker images which are obtained using the plurality of imaging devices,

wherein the image integration means integrates thc imaging regions such that identical markers in the overlapped imaging regions are matched, to thereby form an integrated image.

2. The sensor of claim 1, said sensor comprising a display for displaying an image obtained by each imaging device.

3. The sensor of claim 1 or 2 wherein said tactile section comprises a large area tactile section which is formed by combining a plurality of small area tactile sections.

4. The sensor of claim 3 wherein the tactile sensor comprises a unit comprised of one small area tactile section and one imaging means corresponding to the small area tactile section and the tactile sensor is formed by combining a plurality of the units.

5. The sensor of any one of claims 1 to 4 wherein said tactile section is comprised of a transparent elastic body and a plurality of groups of markers provided therein, each marker group being made up of a number of colored markers, with markers making up

different marker groups having different colors for each group, and the imaging device taking an image of the behavior of colored makers in the transparent elastic body when an object contacts the surface of elastic body.

6. A method for obtaining a marker image using an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and an imaging means for obtaining a marker image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body, said method comprises steps of:

providing a plurality of imaging devices as the imaging means and obtaining a partial marker image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region; and

forming an integrated marker image by integrating the partial marker images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

7. The method of claim 6 wherein said tactile portion comprises a transparent elastic body and a plurality of marker groups provided in said body, each marker group is comprised of a number of colored markers, with markers constituting different marker groups having different colors for each group, and said imaging device takes an image of behavior of colored markers when said curved surface of elastic body is contacted by an object.

8. The method of claim 6 or 7 wherein calibration of the respective imaging device is conducted using the markers.

9. A method for integrating a marker image, which is employed in an optical tactile sensor comprising a tactile section having a transparent elastic body and a plurality of markers provided therein, and a plurality of imaging devices for obtaining a marker

image by photographing behavior of markers when an object contacts the sensing surface of the transparent elastic body, said image integration method comprising the steps of:

obtaining a partial image by photographing a partial region of the transparent elastic body using each of the plurality of imaging devices such that each imaging device has an overlapped imaging region; and

integrating the partial images obtained using the imaging means such that identical markers in the overlapped photograph regions are matched.

10. A method of reconstructing force vector using the sensor of claim 5, said method comprising the steps of:

obtaining a marker image by taking an image of behavior of colored markers when an object contacts a contact surface of the elastic body;

obtaining information relating to the marker behavior from the marker image, said information being more than the number of force vectors to be obtained; and

obtaining force vectors as outputs by inputting said obtained information relating to the marker behavior to a transfer function,

wherein said obtaining force vectors calculates force vectors omitting information relating to behavior of the marker that has low extent of contribution to force vector calculation.

11. The method of claim 10, said obtaining force vectors comprising calculating force vectors using only information relating to behavior of markers in the vicinity of a position where it is desired to obtain force vectors.

12. The method of claim 11, wherein said position comprises one or more sampling points.

13. The method of claim 12, said method further comprising the steps of:

arranging a plurality of sampling points around said position;

obtaining force vectors acting at the sampling points at and around said position using information relating to marker behavior in the vicinity of said position; and

adopting only force vectors acting at said position in the calculated force vectors.

14. The method of claim 13, wherein the sampling points are arranged more sparsely as separation from said position.

15. The method of claim 10, wherein said obtaining force vectors comprising calculating force vectors omitting elements that are close zero in elements of the matrix.

16. A method of reconstructing force vector using the sensor of claim 5, said method comprising the steps of:

obtaining a marker image by taking an image of behavior of colored markers when an object contacts a contact surface of the elastic body;

obtaining information relating to the marker behavior from the marker image, said information being more than the number of force vectors to be obtained;

setting a small region of a specified size in the marker image and arranging a plurality of force vector sampling points inside and outside the small region;

calculating force vectors acting on the sampling points by supplying marker information inside the small region to a transfer function; and

adopting force vectors acting on at least some sampling points of the plurality of sampling points arranged inside the small region.

17. The method of claim 16, wherein the sampling points are arranged densely inside the small region, and arranged sparsely with distance from the small region.

FIG.1

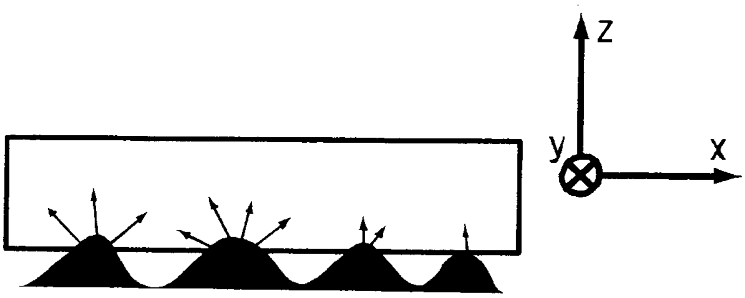


FIG.2

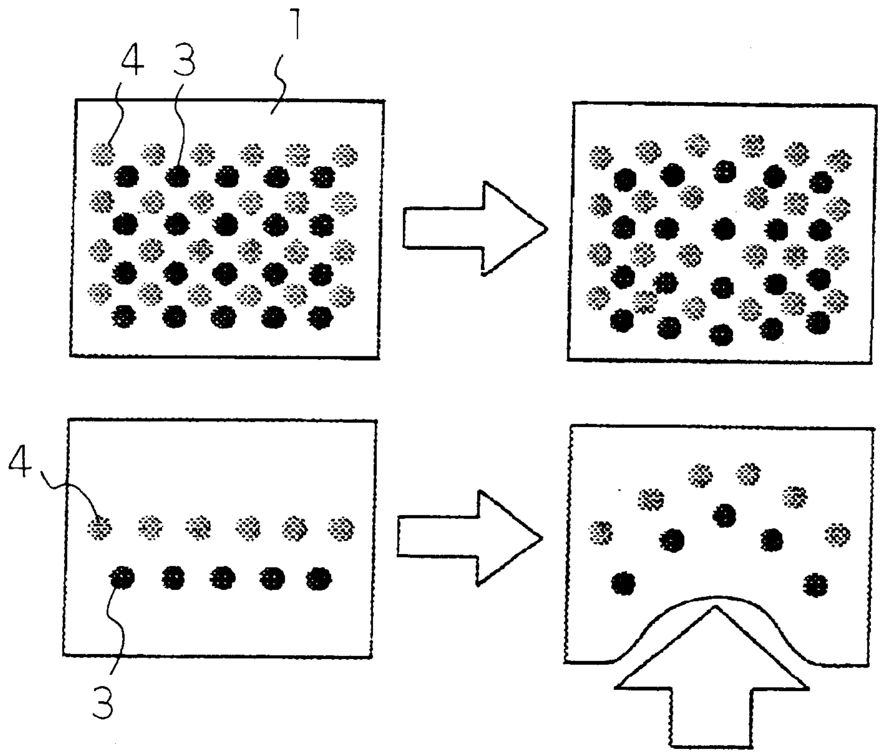


FIG.3

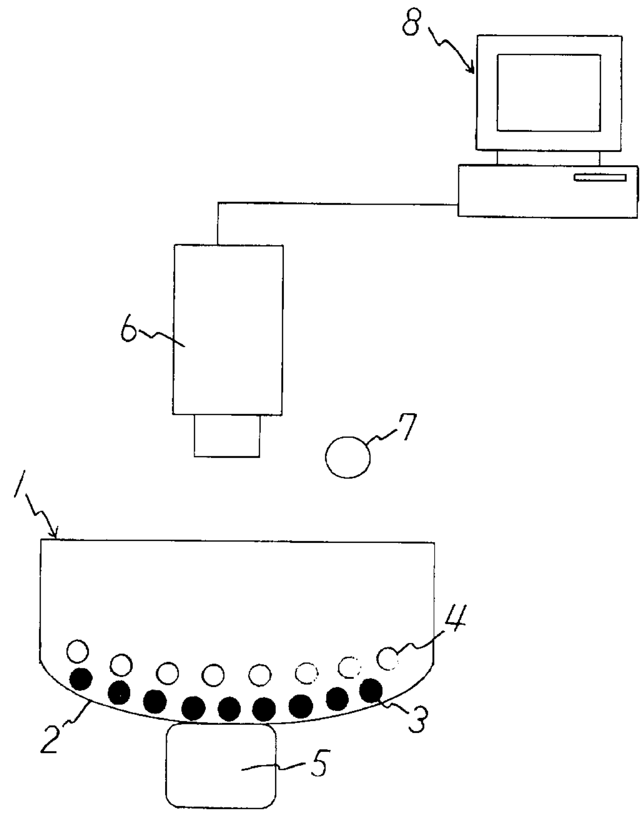


FIG.

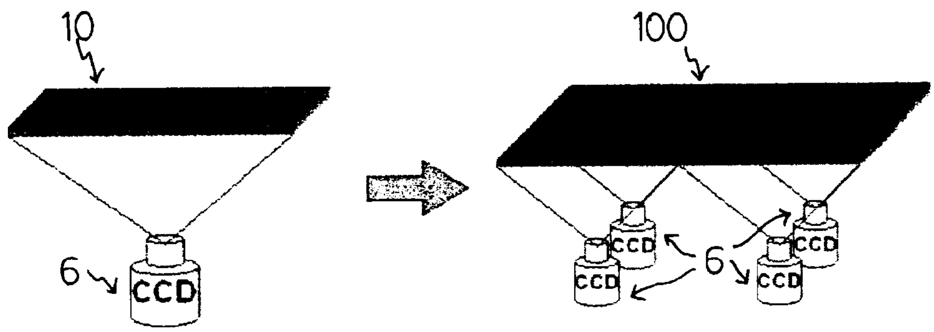


FIG.5

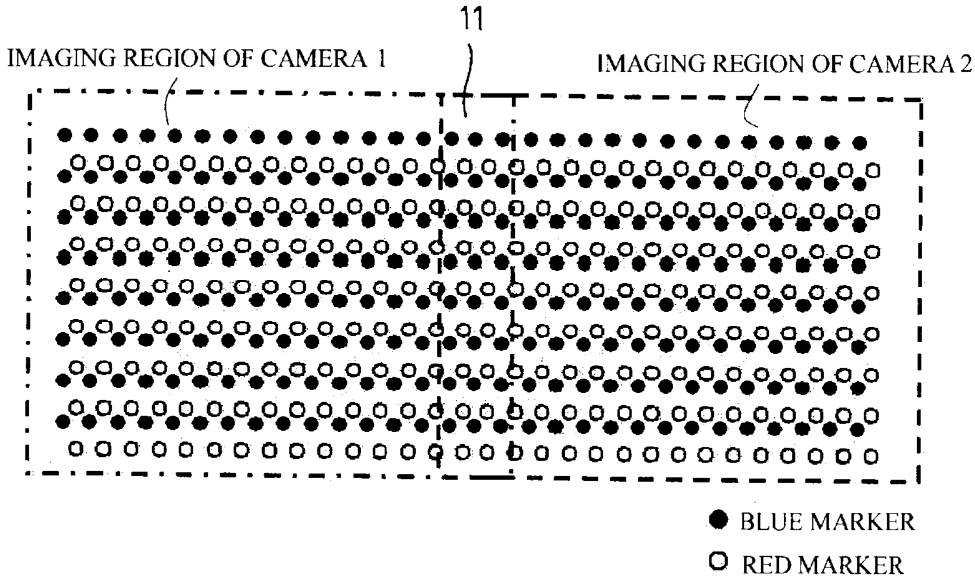

11
IMAGING REGION OF CAMERA 1
IMAGING REGION OF CAMERA 2
BLUE MARKER
RED MARKER

FIG.6

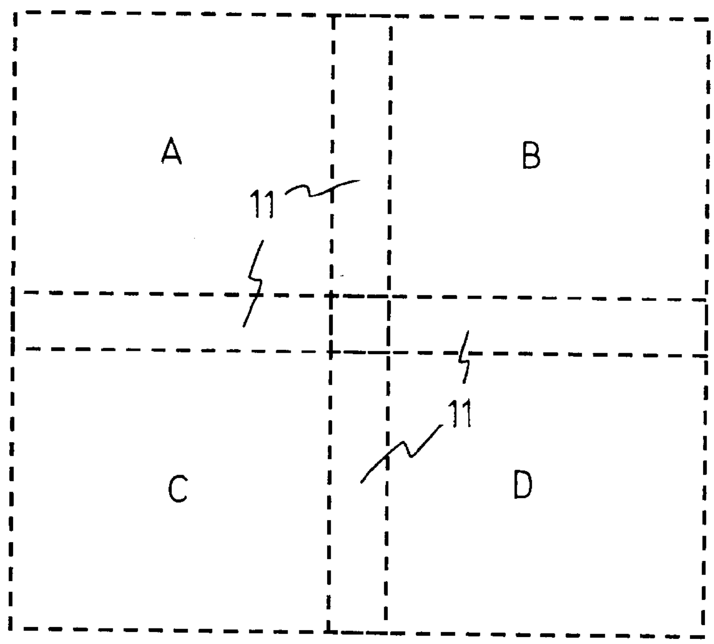

A
B
11
11
C
D

FIG.7

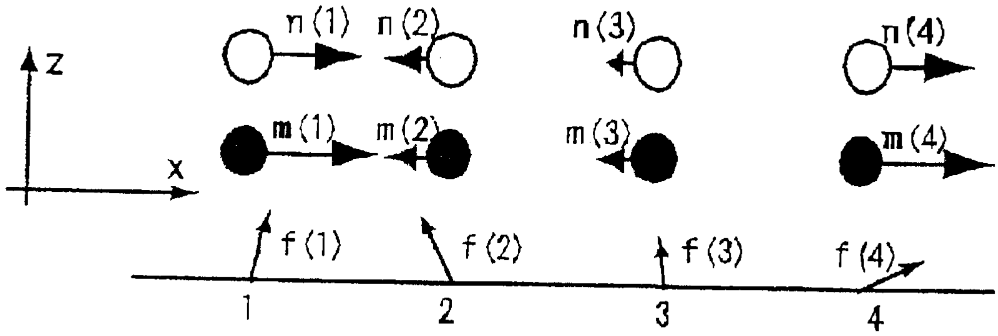

z
x
n (1)
n (2)
n (3)
n (4)
m (1)
m (2)
m (3)
m (4)
f (1)
f (2)
f (3)
f (4)
1
2
3
4

FIG.8

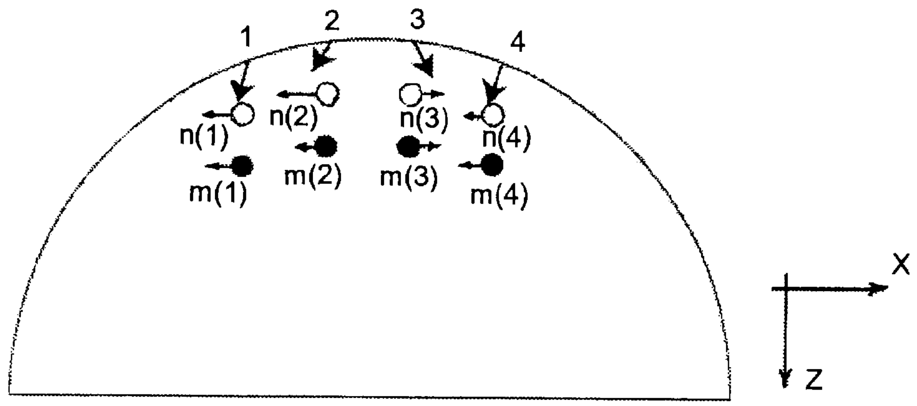

1
2
3
4
n(1)
n(2)
n(3)
n(4)
m(1)
m(2)
m(3)
m(4)
X
Z

FIG.9

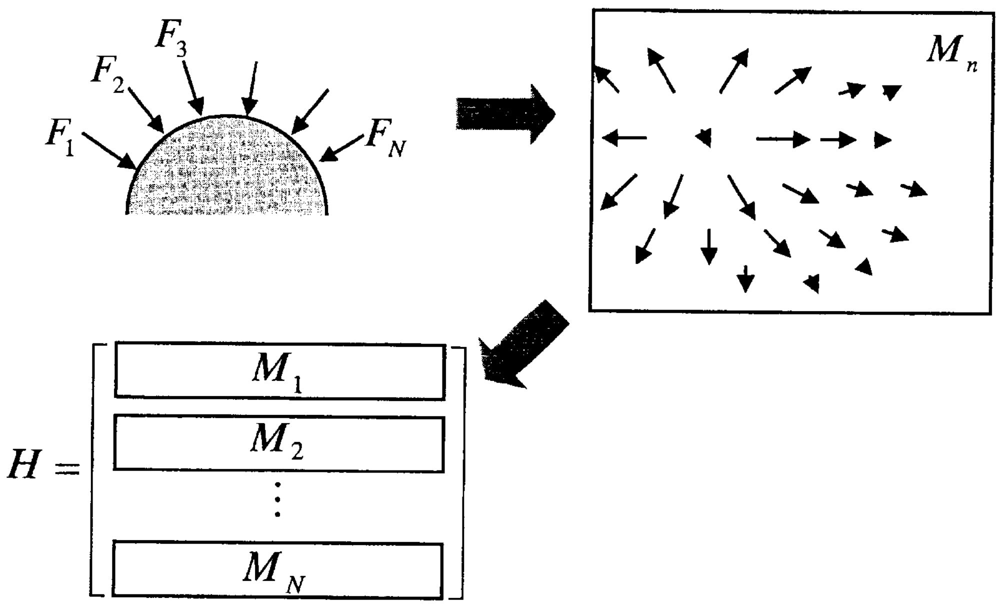


FIG.10

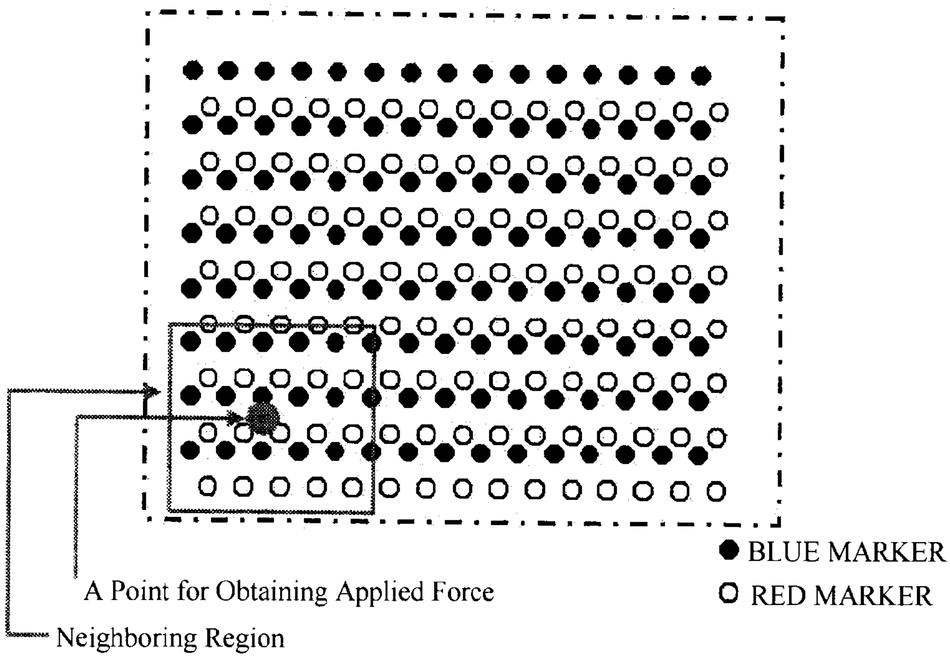
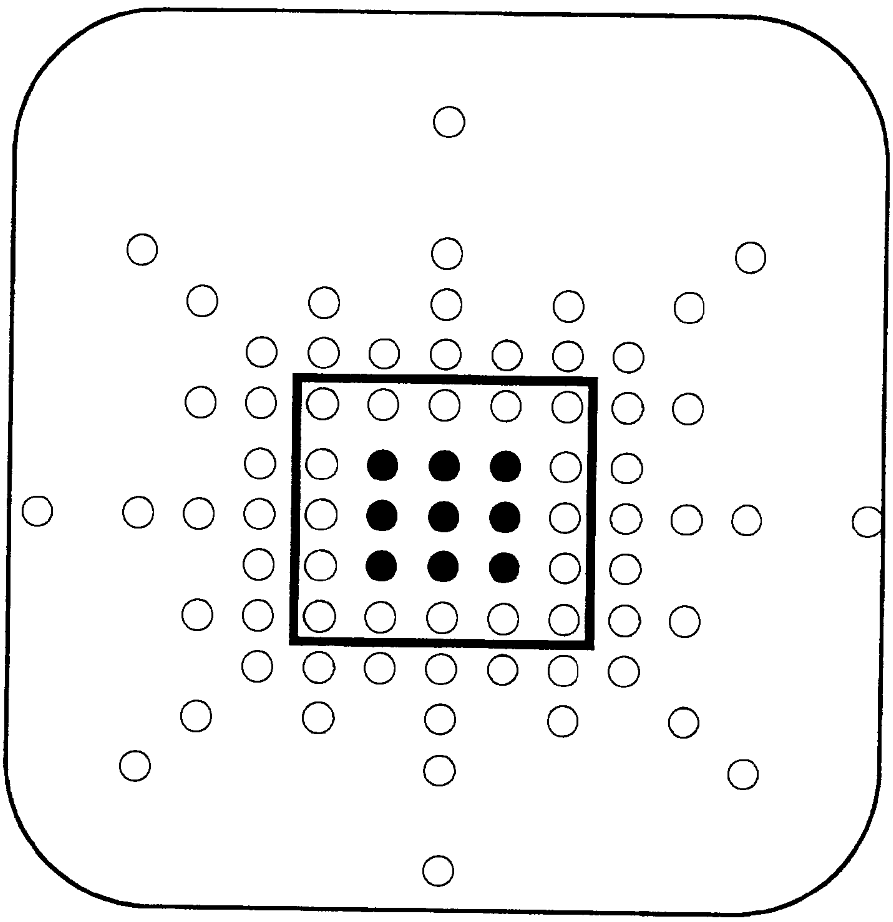

BLUE MARKER
RED MARKER
A Point for Obtaining Applied Force
Neighboring Region

FIG.11



●○ : Force Sampling Points
● : Computational Results used after computation

FIG.12

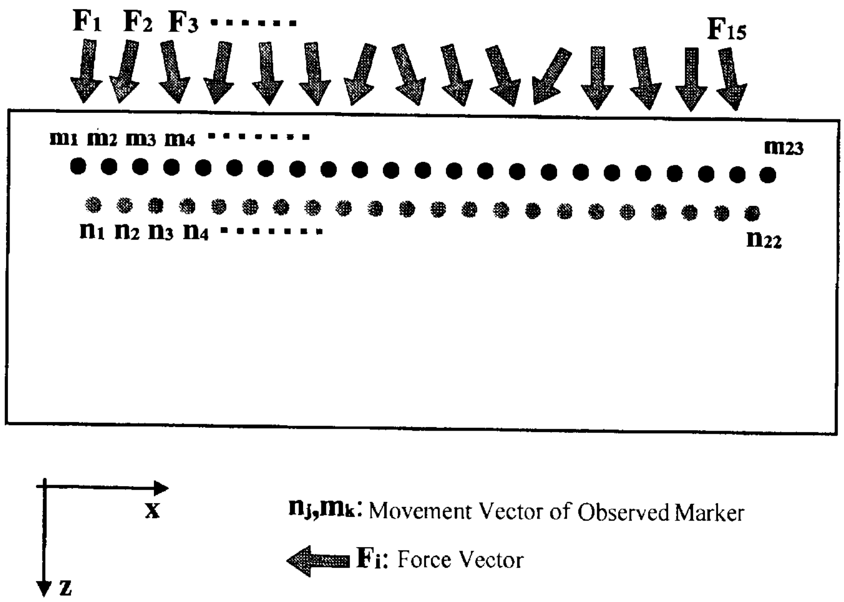

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.13

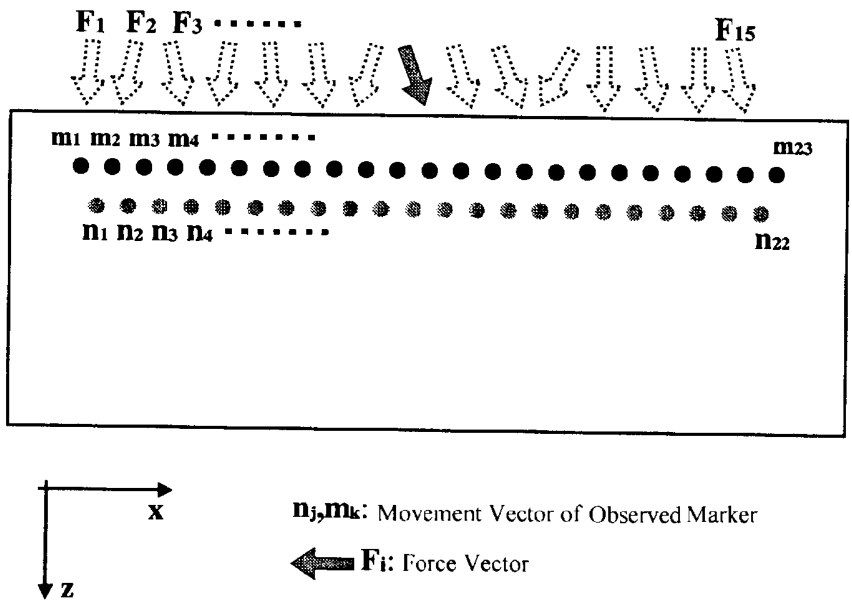
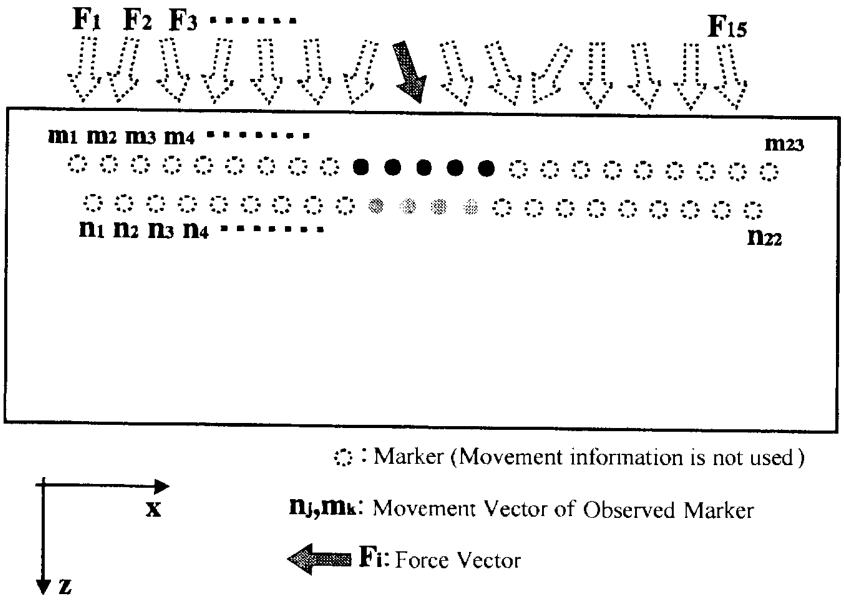
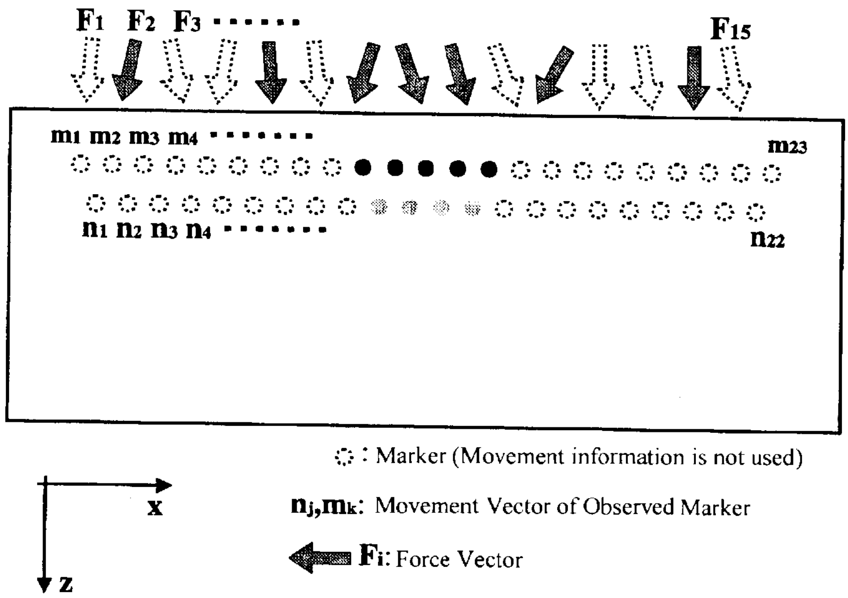

F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.14



F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
: Marker (Movement information is not used)
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.15



F1 F2 F3 ......
F15
m1 m2 m3 m4 ....
m23
n1 n2 n3 n4 ....
n22
: Marker (Movement information is not used)
x
z
nj,mk: Movement Vector of Observed Marker
Fi: Force Vector

FIG.16

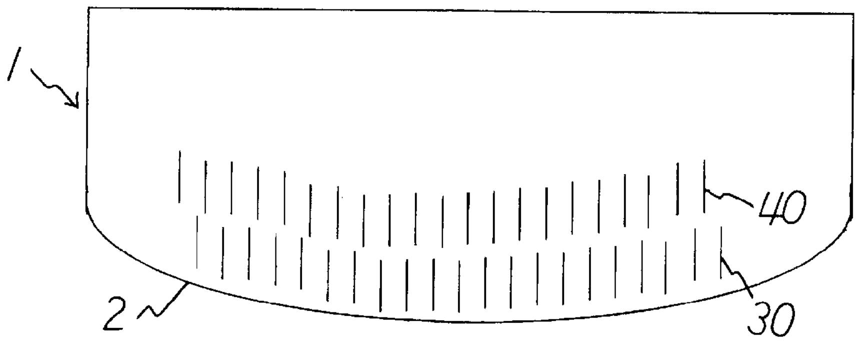
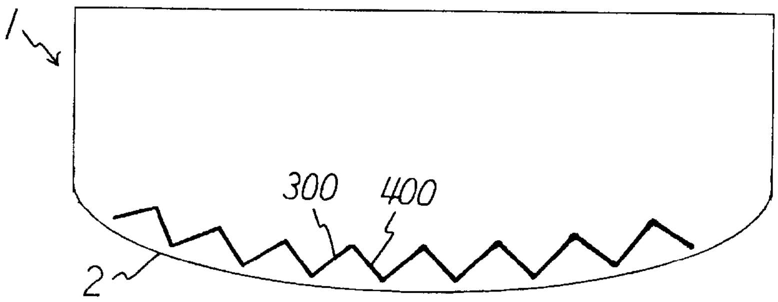


FIG.17



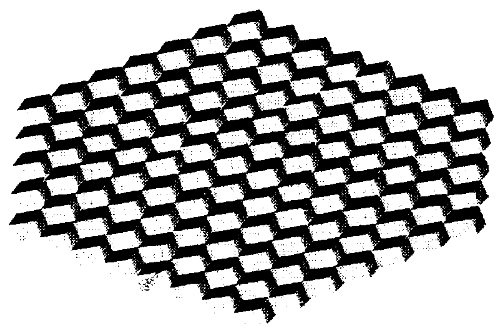


FIG.18

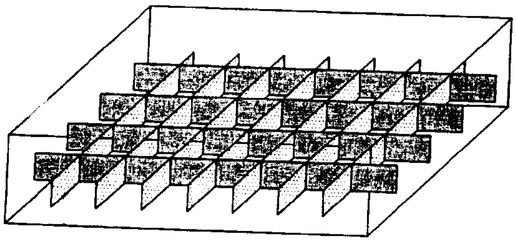


FIG.19