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Multifingered dextrous robotics hand design and control: a review

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SUMMARY

During the last two decades a large amount of effort and attention has been paid to the problem of designing and controlling dextrous robotics hands. The possible application background ranges from telerobotics to upper limb prosthetics, while actual industrial developments are mainly limited to specific grippers and tools. Classical problems related to dextrous hand design are kinematics of multifingered hands, development of proper actuation technologies and redundant tendinous systems for transmission. As far as hand control is concerned, grasp preshaping, planning and synthesis are of major concern, while sensor guided hand operation is still a matter of research. The present work reviews the above mentioned hand design and control issues trying to throw some light on the Babel-like confusion encountered when looking at present literature on dextrous hand design and specially control. Most actuation and transmission technologies, as well as control approaches, are studied and classified.

KEYWORDS: Dextrous robotics; Hand design; Control

1. INTRODUCTION

Research on grasping and manipulation with dextrous artificial hands is a quite mature area of knowledge whose beginnings date back to the early 70s. Since then, a number of research groups have addressed different aspects of the problem, from hand design to control issues.

Already on April, 1982, in the context of a workshop held at MIT,[1] it was pointed out that "the current actuation technology provides perhaps the most serious, long term impediment to artificial hand design". The same statement holds 15 years after this meeting. In fact, current actuation technologies fail to provide efficient, high power density actuators suitable for artificial hand design. The lack of adequate actuation technologies directly affects the design of dextrous hands. If dexterity is to be increased, a larger number of active joints is needed, as a consequence bulky solutions are obtained. Depending upon the application this may or may not be acceptable. In fact, as pointed out by Pfeiffer,[2] one of the most interesting and practical backgrounds for the development of dextrous hands are prosthetic applications. The need in this application field of aesthetic, light solutions is obvious.

Hand design is one problem, the other problem is hand control. Also in the context of the workshop on the design and control of dextrous hands a variety of issues were outlined requiring further study. Kinematic issues regarding number of fingers per hand and number of joints per finger have been thoroughly studied in the past years. From kinematic considerations, it is possible, for instance, to determine the minimum number of fingers for grasping to be three, while, if manipulation with regrasping is the goal a minimum of four fingers are needed. Control aspects of the manipulation with dextrous hands is also one of the key factors to be developed. The integration of tactile and force information for individual finger control, the combination of information from different fingers to guide the hand action are still not well known. Applications of force control algorithms can be improved by attempting compliance or stiffness control schemes.

In general, two different kinds of hand operation can be addressed, namely, grasping and manipulation. Grasping could be understood as the combination of procedures and operations needed to hold an object in a static position with respect to the hand itself. On the other hand, manipulation requires the coordinated motion of the fingers to manipulate the object within the hand. Therefore, manipulation can be regarded as a dynamic grasping and in fact it could be understood as a generalisation of grasping. The distinction between grasping and manipulation as a classification of manipulative hand movements was proposed in terms of extrinsic and intrinsic movements of the hand by Elliot *et al.*[3] Extrinsic movements, i.e. grasping, define movements of a prehended object by displacement of the hand as a whole, while intrinsic movements, i.e. manipulation, define motion of the prehended object within the hand.

Different authors propose different stepwise approaches to the manipulation planning. Pfeiffer[2] proposed a threefold approach to the manipulation planning problem: trajectory planning, grasp planning and hand placement. While the trajectory planning allows for the prescribed motion of the object and the determination of external forces, the grasp planning assures finger force optimization and overall grasp optimization. On the other hand, Reynaerts, in a very comprehensive study of the problem of grasping and manipulation with dextrous hands,[4] proposes also a threefold, task-oriented stepwise approach, namely, grasp preshaping and planning, object equilibrium and stability, and manipulation. In his work, Reynaerts also points out

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several trends in current manipulation research. One of these fields of research could be the so-called graspless manipulation. While in the above approximations, grasping is a previous step to manipulation, in operations like pushing no grasp is performed previous to manipulation. Another concept that is gaining acceptance is that of whole-hand manipulation, where the whole enveloping surface of the fingers and palm is used to increase the dexterity. In fact, whole-hand manipulation and whole-arm manipulation, as proposed by Salisbury,[5] are similar problems if different manipulation tools are considered.

The aim of this work is to thoroughly review the current state of the art on the main topics related to dextrous manipulation, viz. hand design and hand control. The next section will focus on current issues of hand design regarding kinematics of motion and kinematics and dynamics of actuation. Section 3 will review control issues.

2. HAND DESIGN

2.1 *Kinematics*

In designing mechanisms, and in particular multifingered artificial hands, it is desirable to have task-related measures of their kinematic performance. When manipulating objects with multfingered hands we are concerned either with the relative motion of the object with respect to the palm if our goal is manipulation and dynamic grasping, or with the lack of relative motion if we are interested in grasping. According to these kinematic issues several indices or measures have been defined and proposed. In reference [6], the authors define *Mobility* and *Connectivity* to study the grasping and manipulation capabilities of multifingered hands.

The mobility, M, of a kinematic system composed of a number of serial and parallel links is defined as the number of independent parameters required to completely specify the position of every body, including the grasped or manipulated object, in the system. The computation of mobility for a given mechanism is worked out according to Grübler's expression:

$$M \geq \sum_{i=1}^{n} f_i + \sum_{j=1}^{m} g_j - 6L \tag{1}$$

where f_i is the number of degrees of freedom, *dof*, corresponding to joint i, g_j is the number of degrees of freedom at the j contact point and L is the number of independent loops in the system.

On the other hand, the connectivity between two given bodies is defined as the number of independent parameters required to completely specify the relative position of these two bodies. Mason *et al.*[6] defined the connectivity between the palm and the manipulated object under two different joint conditions, viz. under free motion of every joint, C; and under blocked joints, C'. With these definitions it is easy to see that, for manipulation purposes, it is desirable to have a connectivity $C=6$ which means, for small displacements, that the grasped object can be effectively manipulated in all directions (three linear displacements plus three rotations). On the other hand, for grasping purposes, a connectivity $C' \leq 0$ is desirable since under this condition the object can be completely constrained. Under strict $C' < 0$, the object would be overconstrained and the internal force distribution can be used to stabilize the grasp as we will see later on.

Mason *et al.*[6] made an extensive study of possible kinematic configurations for a multifingered hand under the assumption of having a maximum of three fingers with a variable number of joints per finger. The study considered three kinematically different contact configurations: The first approach considered contact between bodies allowing 5 *dof* which corresponds to point contact without friction. In a second step, they allowed for 4 *dof* contacts corresponding to line contacts without friction. Eventually they studied *soft finger* contacts which in turn allow three *dof*. They found a total of 39 configurations or designs meeting the conditions for grasping and manipulation.

2.1.1 Dexterity of manipulation. When considering hand manipulation problems a number of matrices are of interest. Similarly to the Jacobian matrix defined for manipulators, J, that relates joint velocities to end-effector velocities, when considering dextrous artificial hands, the grip transform, $\mathbf{G}$, is introduced. The grip transform allows us to determine the overall force exerted on the grasped object as a function of the joint torque applied to every joint of the fingers. If we define $f(\theta)=\mathbf{x}$, where $f(\theta), \mathbf{x} \in R^N$ and N are the kinematics expression relating manipulation coordinates to joint coordinates, the current position of the grasped object and the number of degrees of freedom of the object, respectively, then we have:

$$\mathbf{G}\delta\theta = \delta\mathbf{x} \tag{2}$$

in this equation, $\mathbf{G}$ represents the grip transform comprising the partial derivatives of $f(\theta)$ with respect to $\theta\tau_i$.

Similarly defined is the grasp Jacobian matrix, $\mathbf{J}_g$, as the matrix relating the manipulation velocity of the object and the velocity of the points of contact between fingers and grasped object. Since every finger of the dextrous hand can be considered as a manipulator, a third matrix of interest can be defined, the hand Jacobian matrix, $\mathbf{J}_\mathrm{h}$. The hand Jacobian matrix, $\mathbf{J}_\mathrm{h}$ relates contact point velocities to joint velocities. As a consequence of the definition of these matrices, the relationship among them is represented in Figure 1. The hand Jacobian matrix can be constructed from single finger Jacobian matrices arranging them in a diagonal matrix:

$$\mathbf{J}_\mathrm{h} = \begin{bmatrix} J_{f1} & 0 & \dots & 0 \\ 0 & J_{f2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & J_{fn} \end{bmatrix} \tag{3}$$

where J_{fi} corresponds to the i-th finger.

Manipulability measure. Together with the mobility and connectivity measures, some other indices have been used to describe the manipulation ability of a multifingered hand. In particular, the *Manipulability* has been recursively used in the literature. Even when there is no unique definition, a

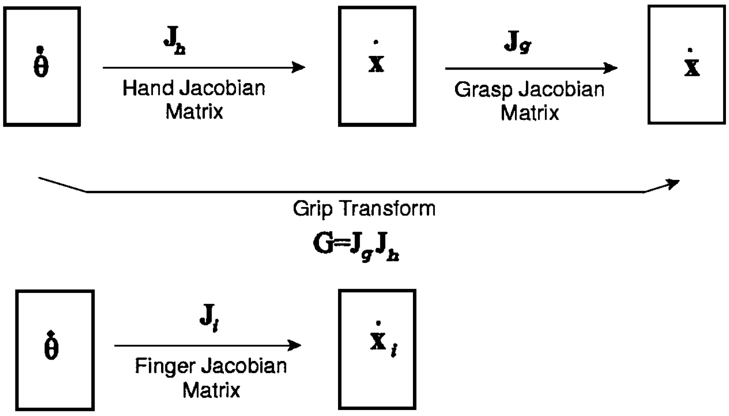


Fig. 1. Relation among different matrices.

useful interpretation due to Cutkosky,[7] is that of the ability to impart arbitrary motions to the object from a given point in the workspace. In this regard Yoshikawa[8] gave a quantitative measure of the manipulability as the ability to impart arbitrary motion – to the grasped object in the case of multifingered hands or to the end-effector when considering manipulator arms – as related to the application of joint motions. The general expression of Yoshikawa's manipulability index for a manipulator is:

$$w = \sqrt{\det J(\theta) J^T(\theta)} \tag{4}$$

where w is the measure of manipulability and $J(\theta)$ is the Jacobian matrix relating joint velocities to manipulation velocities. It can be shown that matrix $J(\theta)J^T(\theta)$, due to its positive-definiteness, represents the equation of an ellipsoid. The isotropy of the kinematic transformation provided by the manipulator is related to the eccentricity of this ellipsoid in such a way that the higher the eccentricity the lower the isotropy of transformation.[9] Moreover, w is proportional to the volume of the ellipsoid which becomes zero as the excentricity increases. As a consequence, w gives a measure of the proximity to a singular point within the workspace of manipulation, see Figure 2. It can be shown that the Yoshikawa's manipulability measure is equivalent to the product of all singular values of J.

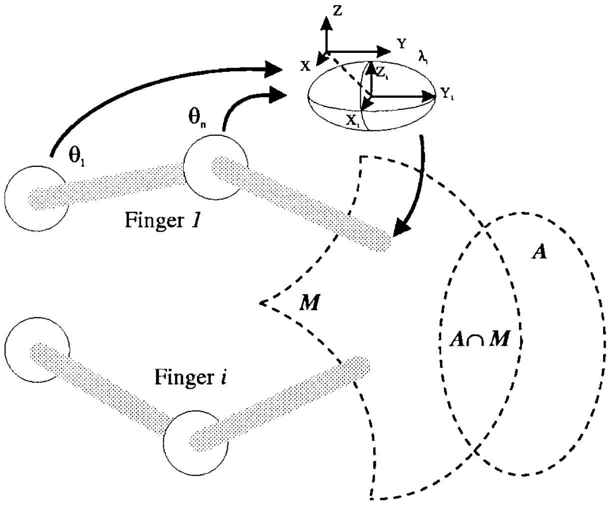


Fig. 2. Local and global measures of manipulability.

The same index can be defined for dextrous hand manipulation with a slight modification of the definition:

$$w = \sqrt{\det GG^T(\theta)} \tag{5}$$

The manipulability index of Yoshikawa was used in reference [8] to determine the best grasping postures of a three-phalanx finger as well as to determine the best ratio between the length of the finger links.[9]

Lower singular value of G. The lowest singular value of G can be regarded as a measure of the dexterity of the manipulation process, as proposed by Shimoga[10] and based on similar studies on redundant manipulators from Klein and Blaho,[11] Maciejewski and Klein,[12] and Klein.[13] In a singular value decomposition of **G** (see equation 6) the lowest singular value of G is the lowest non-negative element of the diagonal matrix Σ.

$$\mathbf{G} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathrm{T}} \tag{6}$$

In the proximity of singularities, the determinant of **G** (or the determinant of GG^T) becomes very low and depends critically on the lowest singular value due to abrupt changes of this singular value. As a consequence, the higher the lowest singular value the more dextrous manipulation is possible.

Deviation of joint angles. For a given grasp configuration, it is desirable that joints are far enough from their limits so that a large range of motion is available for regrasping. This way, if we define θ_{0i} as the mid range configuration for joint i, a measure of the deviation of joint angles from the mid range configuration can be defined as:

$$\theta_{dev} = \sum_{i=1}^{m.n} (\theta_i - \theta_{0i})^2, \tag{7}$$

where θ_i and θ_{0i} are position and mid range position of joint i respectively, and m and n are numbers of fingers and numbers of joints per finger, respectively. If $\theta_{\mathbf{dev}}$ is minimised for a given grasp configuration we are somehow maximising the dexterity of next regrasping operations.

Requirement of Joint torque. As seen previously, for a given grasp configuration defined by **G**, the force exerted on the grasped object is related to the applied torque by:

$$\tau = G^T f_{ext} \tag{8}$$

The optimisation of grasp configuration, or for a given grasp configuration the optimisation of mechanism design, can be viewed as the process of minimising the required joint torque to obtain a prespecified force on the object. This process is a way of solving the configuration redundancy by minimising the required torque.

The process of minimising the torque for a given exerted force is equivalent to finding a grasp configuration that, for a unit torque vector, produces maximum force in the required direction. The unit torque vector meets the following expression:

$$\|\tau^2\| = \tau^T\tau = (\tau_1^2 + \tau_2^2 + \ldots + \tau_n^2) = 1 \tag{9}$$

using 8 this equation transforms to an ellipsoid in R^N:

$$f_{ext}^T (GG^T) f_{ext} = 1 \tag{10}$$

This ellipsoid is known as the force ellipsoid of the grasp configuration. The length and direction of its axes are given by the eigenvalues and eigenvectors of $\mathbf{GG}^\mathbf{T}$, respectively. The direction of the largest eigenvalue represents the direction of maximum allowable exerted force. The grasp configuration can be selected so that the largest axis of the ellipsoid is directed according to the direction of maximum required force, so that the exerted force can be applied with a minimum joint torque.

A graphical comparison of the different dexterity measures is given in Figure 3. In this figure we can see how the measures are related among them for configurations close to singularities.

The manipulative measures as defined above give a local information of the transformation between joint and manipulation velocities. A more general manipulability measure was defined by Pons *et al.*[14] in order to account also for the distribution of the local manipulability measure of Yoshikawa throughout the manipulator's workspace. This time the global manipulability measure was defined as shown in Eq. 11:

$$gm = \tau\bar{w} \tag{11}$$

where,

$$\tau = \frac{\text{vol. } \mathscr{A} \cap \mathfrak{M}}{\text{vol. } \mathfrak{M}} \tag{12}$$

with $\mathscr{A}$ the space region required for manipulation and $\mathfrak{M}$ the effective manipulation region with the actual multifingered hand kinematics; and $\bar{\omega}$ is the mean value of the Yoshikawa's measure.

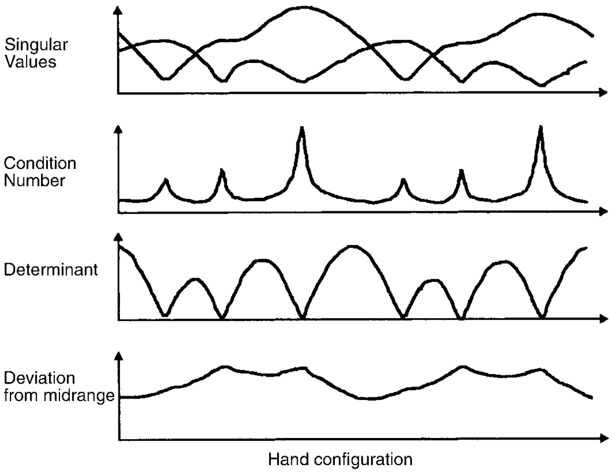


Fig. 3. Comparison of dexterity measures.

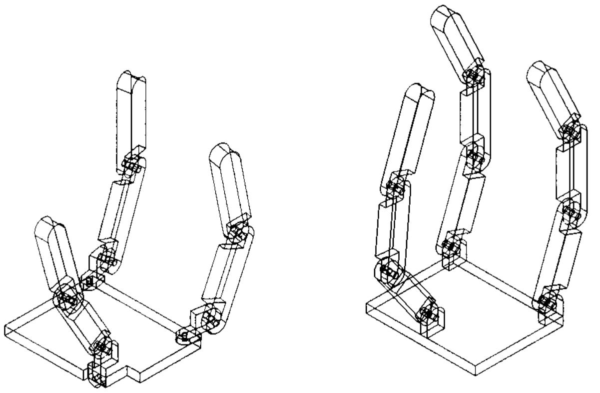
The new metric depends on the Jacobian matrix of the mechanism and on the workspace of manipulation as related to the workspace required by the task (see Figure 2) and was used in reference 9, to optimally design a parallelogram manipulator.

There is a huge amount of work devoted in the past decades to studying dexterity of manipulation. Covering it is completely out of the scope of this paper; however, to the reader interested in this matter some references of interest can be given. In particular, issues related to isotropy and configuration of the Jacobian and grip transform matrices can be found in reference 15. Some additional indices for measuring dexterity both for planar manipulators and for fingers are addressed by Gosselin in references 16 and 17. Finally, manipulability is thoroughly studied by Doty in reference 18.

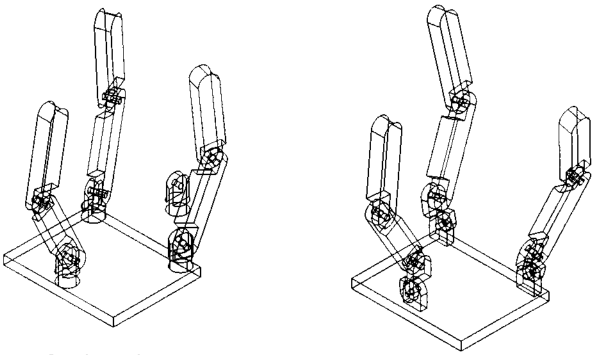
2.1.2 Hand configuration. Even when all these theoretical kinematic measures provide tools for finding adequate configurations of multifingered hands, it would be too presumptuous not to be looking at the human hand (after some millions of years of evolution) as a model to guide the design of technical hands. Moreover, this becomes compulsory when dealing with technical hands for prosthetics. Human fingers have four basic kinds of motion except the thumb that has a fifth very specialized motion: *Flexion* of the finger is the motion of closing the finger towards the palm, while the opposite motion, corresponding to opening the hand is called *extension*. When we consider the middle finger as the axis finger of the hand, the motion of other fingers towards this one is called *adduction*, while the opposite motion is called *abduction*. The fifth motion that distinguishes the thumb from all the other fingers and the human hand from other primates' hands is the *opposition*. In this motion, the thumb opposes all the other fingers allowing a whole set of grasps (see reference 4 for a more detailed description of the human hand manipulation).

According to the kind of motion the kinematic chain of artificial hands allows, they can be classified in four types which are described below. In order to see more easily the configuration of each hand type, Figure 4 shows a schematic representation based on the work of Reynaerts[4] of their kinematics.

- *Flexion hands.* This is the most simple kinematic design in which all the fingers are composed of links with parallel-axis rotational joints.



Opposition **Flexion**



Cylindrical **Adduction-Abduction**

Fig. 4. Kinematic configuration of artificial hands: opposition, flexion, cylindrical and adduction-abduction.

- *Cylindrical hands.* This kinematic type combines the horizontal axes of the previous design with a vertical axis for each finger in the direction of the first phalanx.
- *Adduction-Abduction hands.* This hand combines one or more horizontal axes to provide flexion-extension with another horizontal axis perpendicular to the previous ones, so that adduction-abduction is provided. A number of variations are still available even using a given type of hand. For instance, in *Menzel*'s PhD thesis[19] the design of a four-fingered, three-phalanx per finger, adduction-abduction type hand is presented. The total number of active joints is, however, 9 since the last two joints in each finger corresponding to the distal interphalangeal joint, DIP, and the proximal interphalangeal joint, PIP, are coupled with an approximate ratio of 1:1. Another interesting development within this type of hands is the so called Standford-JPL hand, which is actually commercially available. It is a three-fingered, three phalanx per finger hand and therefore it is limited for performing regrasping operations.
- *Opposition hands.* This is the kinematic structure that most resembles human operation. It combines either the flexion or the adduction-abduction with an additional rotational axis that allows performing opposition. To this type of hands belongs the well known UTAH-MIT hand. It is a four-fingered hand with four joints per finger all of them totally active. Recently, a second prototype of the MIT hand was developed by Matsuoka.[20] This last prototype was designed and developed within the context of studying embodiment in human grasping and manipulation. It has a simpler kinematical structure in which three fingers and a thumb are incorporated. Each finger has two horizontal *dof* plus a third at the finger base.

The number of hand developments is extremely large. For a more comprehensive description of the different designs see references 21 and 4.

2.2 *Actuation*

As mentioned in the introduction, actuation technology is the main limit when designing dextrous robotic hands. If bulky solutions are not acceptable, two solutions are left, namely, first using less actuators than the actual number of degrees of freedom of the hand; secondly, placing actuators somewhere behind the hand and using tendon systems to transmit the motion to the joints. The first solution led to the so called underactuated systems. Let us briefly analyse underactuated systems in the first place, to focus later on tendinous systems.

2.2.1 Underactuated dextrous hands. As mentioned before, the use of underactuated approaches to solve grasping problems with dextrous hands is a consequence of the lack of high power density, efficient actuation technologies. An underactuated hand is one in which the number of actuators is lower than the number of degrees of freedom.

Underactuation can be easily achieved by linking the motion of the joints of a finger or linking the motions of one finger to another. If the design of the hand only allows fixed coupling among joint or fingers the resulting mechanism has effectively the same number of *dof* as the number of actuators, the geometry of the enveloping surface of the hand is fixed and thus no adaptation to object geometry is possible. This approach is common to a number of robotic and prosthetic hands.

Motion coupling between joints in a finger can be achieved by a variety of mechanisms. For light solutions two basic mechanisms are used, namely, rigid bar linkages and tendon transmission through pulleys. In particular, the solution based on rigid bar linkages was used by Vinet[22] to link the motion of the first and second phalanx on their prothetic hand. For a given fixed transmission ration exact dimensions of the bar linkages are obtained by constrained optimization techniques. The solution obtained is compact and can be optimum also with regard to singular mechanism configurations and required force in linkages for a given joint torque.

The second solution is based on tendons transmission between consecutive joints in a finger. This approach is applied also in a number of hand designs as Butterfass[23] and Liu.[24] Since tendons are used some kind of pretensioning should be provided. If pretensioning is provided by linear springs in the tendons, the grasp can become unstable when large forces are applied.

If an actuator would be provided for every joint of a dextrous hand, active adaptation of the grasping envelope could be provided. For the underactuated systems so far presented, no adaptation to object geometry is possible. However, a second family of underactuated systems for which passive adaptation to object geometry is possible can be considered. This last approach has also been used in a number of hand designs and can be classified according to the elements whose motion can be passively adapted. Usually passive adaptation couples in a compliant manner the motion of either joints between phalanxes in a finger or one finger to another.

The second approach was already introduced by Hirose at the Toyo Inst. of Technology,[25] in a hand with two fingers and only one actuator. Tendons are used to drive the hand that can adapt to object geometry. The motion of each fingers are coupled so that compliant passively adjustable independent motion is obtained. In general, any differential mechanism can be used to obtain the passive adaptation between fingers or phalanxes. Most of these differential mechanisms lead to high complexity of the design. However, some simple differential mechanisms can be implemented by using tendons and pulleys. The first approach was introduced by Hanafusa[26] in a hand with three fingers and three actuators. Each finger has passive enveloping surface adaptation to actual grasped object shape.

Both full actuated and underactuated dextrous artificial hands include, in nearly all designs, either electromagnetic actuators or pneumo-hydraulic actuators. Among these actuators, electromagnetic ones are the most widely used. They have both good stiffness and bandwidth, and likewise, the ease of control is a major advantage even when power in electromagnetic actuators is limited by the magnetic characteristics of actual permanent magnets. However, electromagnetic actuation has a clear drawback which is its low power to weight/volume ratio, and therefore bulky and heavy solutions are obtained.

On the other hand, pneumatic actuators exhibit relatively low actuation bandwidth and stiffness and as a consequence, continuous control is complex. Actuation solutions developed on the basis of pneumatic actuators offer low-weight and compact actuators which provide enough force. Hydraulic actuators can be classified somewhere in between pneumatics and electromagnetics. Stiffness is quite good due to the low compressibility of the fluid. Since some degree of compressibility is still found, disturbances can be easily damped. While pneumatic actuators can be used with fluid pressures up to 5–10 MPa, hydraulic actuators can work with up to 300 MPa.

Hydraulics has been used following two different alternatives: existing prototypes are based either on an hydraulic coupling between an electrical motor and the joint or as a tendon system coupled with a hydraulic system. The most common solution is based on electromagnetic linear actuators coupled hydraulically with the driven joint. This is the case presented by Menzel[19] in which by using this technique, electrohydraulic valves are avoided.

Recently some non-traditional actuation technologies have been proposed and developed for dextrous hand operation. Shape Memory Actuation is one of these emerging technologies. The main author[27] proposed in the framework of a European Project, the development of a hand prosthesis based on this actuation technology. Shape Memory Actuators are claimed to provide the best overall power density of all existing driving technologies for small sized actuators. This power density level together with its intrinsic self-sensing capability, makes it possible to obtain very compact prototypes.[28] However, some drawbacks are present in this technology. Displacement levels are quite low and actuation bandwidth is limited by the slow heat transfer processes needed to promote the phase transformation of shape memory alloys. As far as the efficiency of the actuators is concerned, it is still very low as compared to electromagnetic actuators, imposing the main shortcoming for autonomous applications. Additional advantages of this actuation technology, as is claimed by Burdea *et al.*[29] are the absence of frictional parts and the silent operation of these actuators. The combination of low weight and self-sensing capabilities with the high density provides an ideal solution when weight and space are at a premium, provided the energy source is not the problem.

2.2.2 Tendon actuation. When considering conventional actuators bulky solutions are often obtained and therefore they have to be placed somewhere behind the wrist. Motion is always transmitted to the fingers by using tendons or cables. Even when tendons emulate the human motor system the selection of this transmission technology does not rely merely on the imitation of the animal nature. Tendons simplify control problems by providing zero-backlash compliant transmission as reported by *Reynaerts*.[4] When comparing tendon transmission to other forms of power transmission it provides low inertia and low friction alternatives. An additional advantage arises when design flexibility, cost and maintenance are considered.

The crucial aspect when choosing tendon transmission can be schematically shown in Figure 5. As can be seen, tendon routing can be designed to enhance the loading of structures as well as to couple the motion of joints. Figure 5 shows a *centered tendon system* versus a *positively coupled tendon system*. When considering a centered tendon system, tendons of the former joints are passed through the center of rear joints; this way rear joints will not be affected by the tension of tendons corresponding to former joints. As a consequence, the required tension of tendons acting on joints at the root is large.

On the other hand, positively coupled structures are obtained when tendons are routed at one side of the rear joints. The effect is that lower forces are required to withstand a given payload *P*.

Tendinous systems can be classified according to the number of tendons per joint. One of the main difficulties from the point of view of control is the redundancy in tendinous actuation. Redundancy in tendinous systems is defined as the difference between the number of tendons used to drive a set of degrees of freedom and the number of degrees of freedom. In an excellent paper[30] Kobayashi establishes the conditions for a tendon-driven mechanism to be tendon controllable. A system is said tendon controllable if, for a given joint torque, there always exist positive tension forces for producing that torque. Additional discussions are introduced in his work about joint stiffness adjustability of the tendon-driven mechanism.

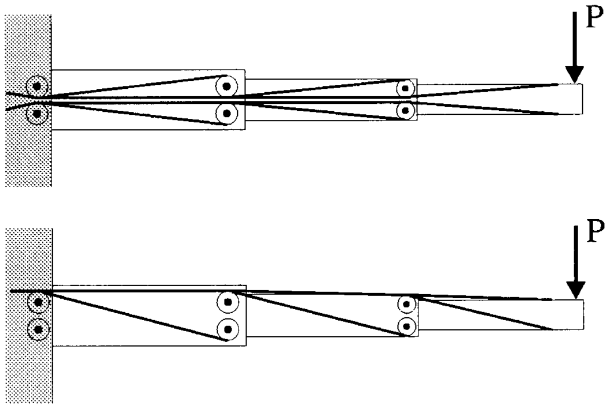


Fig. 5. Centered and positively coupled tendon systems.

One of the main difficulties in controlling tendinous systems is the so-called *unisense permissible forces.* This issue is similar to the problem of unisense forces at contact between a dextrous hand and the grasped object, while in contact forces just pushing forces are possible, but when considering tendinous actuation, just pulling forces are acceptable. The above mentioned classification according to number of tendons per joint is schematically depicted in Figure 6. The following can be said of n, $n + 1$ and $2n$ systems:

- *n-tendon systems.* Two different structural approaches follow kinematically n-tendon systems (see reference 29). In the first approach, Figure 6a, the actuator is used to obtain the flexion motion of the dextrous hand while opening or extension is performed by a pretensioned spring. The second approach, Figure 6b relies on a single actuator with two opposed tendons to perform flexion and extension. A straightforward advantage of these tendinous systems is the reduced set of required actuators as compared to $2n$ systems.

  When considering n-tendon systems an important issue is the need of pretensioning in order for tendons not to go slack when high velocities are used. The approach based on extension springs has an additional disadvantage since part of the flexion force is employed for stretching the spring. As reported by Reynaerts,[4] several papers were published concerning control of n-tendon systems. A quite interesting approach is presented by Kaneko[31] in which a differential torque sensor following the scheme shown in Figure 7 is applied. This specific configuration provides a measure proportional to the tension difference between both tendons, i.e. proportional to the applied torque.
- *2n-tendon systems.* This is the approach that maximizes the flexibility of operation being used for instance to drive the Utah-MIT dextrous hand as presented by Jacobsen.[32] The approach is based on the so-called “agonistic-

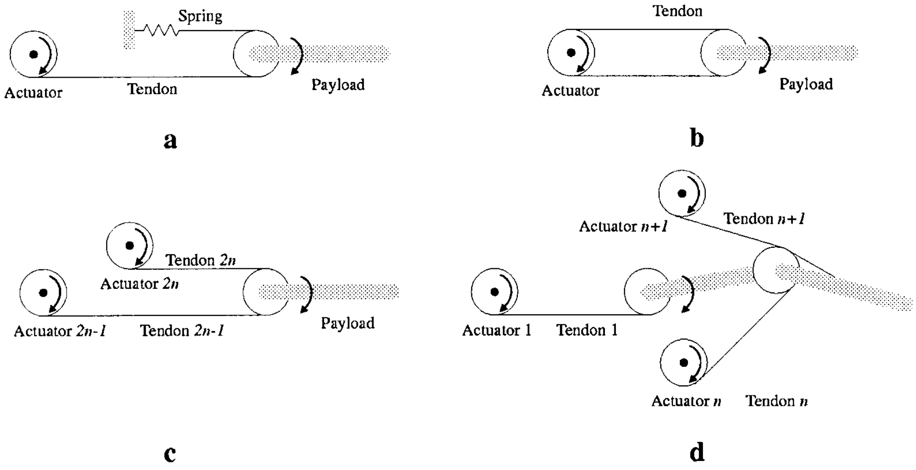


Fig. 6. Kinematics of tendinous systems: (a) Two opposed tendons and one actuator, (b) One tendon-actuator against extension spring, (c) $2n$-tendon system and (d) $n+1$-tendon system.

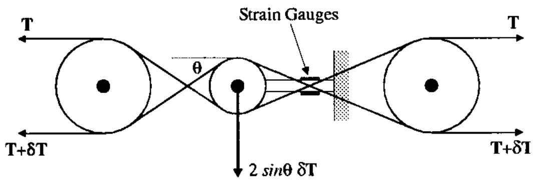


Fig. 7. Difference torque sensor approach to control *n*-tendon systems.

antagonistic” operation of tendons and therefore two actuators together with two tendons per active joint are used as shown in Figure 6c. By using this approach low co-contraction forces are possible and precision and accuracy are enhanced as compared to other configurations. The improved performance is somehow hampered by an increased complexity due to the high number of actuators.

- $(n+1)$-*tendon systems.* The $(n+1)$-tendon system was first introduced by Morecky,[33] as a means of offering the advantage of tendon pretension control while reducing considerably the complexity of the overall system. The $(n+1)$-tendon system uses $n + 1$ tendons and actuators to control n independent joints. Such a scheme is shown in Figure 6d where two tendons are used to flex the finger while extension is provided by a single actuator-tendon. This tendon driven approach has been thoroughly studied in the so-called Stanford-JPL hand.

3. HAND CONTROL

As already pointed out in the introduction, hand control comprises three basic operations, namely, grasp preshaping and planning, grasp synthesis and manipulation. We will now follow this chronological sequence of operation to study the state of the art on control of multifingered artificial hands. However, it is worth noting that when programmed off-line, the order in which these operations are planned can be altered. This is the case presented by Pfeiffer[2] where overall trajectory planning is computed previous to grasp optimisation or synthesis, and then follows hand placement planning.

3.1 Grasp Preshaping

Most of the research devoted in the previous years to multifingered hand control deals with the problem of grasp synthesis that will be treated in the next paragraph. However, as indicated in reference 4, due to the large number of degrees of freedom of multifingered hands it is practically impossible to generate contact location from a simple description of the object to be grasped, the hand and the task. Under these circumstances, hand or preshaping is used as a pre-planner and a number of papers describing the taxonomy of human hand operation appeared in the past decades.

The first work describing the taxonomy of human prehension was due to Schlessinger, back in 1919 and yielded a classification of human grasping capabilities as a function of object size and shape. Schlessinger’s classification has become a classic and describes six basic grasping configuration or primities, namely, cylindrical grasp, spherical grasp, palmar prehension, tip prehension, hook prehension and lateral hip. On the other hand, a classification based on hand surfaces is due to McBride. In his work, McBride differentiates between whole-hand grasping, finger-thumb grasping and palm-digits grasping.

Among all papers devoted to hand preshaping, perhaps the most referenced is Napier’s work on human grasping.[34] He classified prehensile postures according to power and precision grasp, and non-prehensile postures as hook grasp. In 1962, Landsmeer stated an important distinction between grasping and handling objects. It was the first work that introduced in the study of hand taxonomy the concept of manipulation or dynamic grasping. He considered the power grip as the way in which an object can be immobilised within the hand. When considering the objects held between fingers and opposed thumb he used the term precision handling.

Behavioral studies have shown that the kind of grasp is not only affected by size and shape of prehended object as supposed in the works presented above, but also by the task. Regarding this point, *Cutkosky*[7] presented a very comprehensive study of the influence of shape, size and task on the choice of manipulative postures. He ended up with up to 16 kinds of grasp that span all the possible grasping primitives in the context of tool usage from gross to detailed tasks and geometry, from high power requirement to high dexterity tasks and considering different object sizes (see reference 7 for a detailed description of this taxonomy study).

An interesting concept is that of *virtual fingers* as presented by Iberall.[35] Virtual fingers are one or more real fingers working together to solve a problem in a task. According to the concept of virtual fingers it is possible to describe the basic methods of opposing forces to constrain the motion of an object. These three basic methods are shown in Figure 8. As shown in Figure 8a, *pad opposition* consist in the opposition of virtual finger 1 (thumb) and

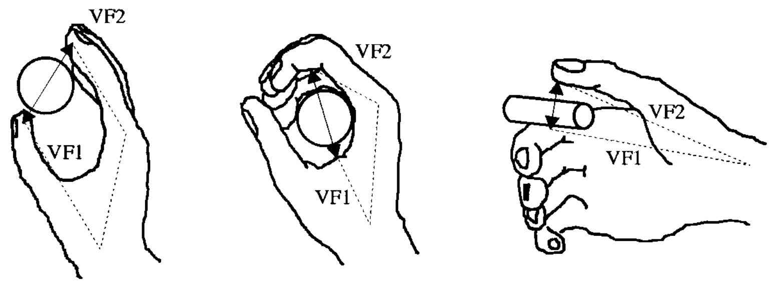


Fig. 8. Concept of “virtual fingers” describing grasp composition.

virtual finger 2 (one or more fingers). This kind of opposition occurs in an axis roughly parallel to the palm and allows great flexibility in fine manipulations at the expense of stability and force. *Palm opposition* use as virtual finger 1 the palm, while virtual finger 2 may comprise any number of real fingers. This time flexibility of motion is sacrified achieving more stability. Finally, *side opposition* is defined between the thumb pad as virtual finger 1 and the side of index finger as virtual finger 2. This time a compromise between flexibility and stability is reached.

Recently, Lyons[36] made use of an approach based on virtual fingers to obtain a classification of encompass (cylindrical), lateral and precision grasps and demonstrated the possibility of hand preshaping by using potential field methods.

When considering off-line programming of grasping and manipulation with multifingered hands, Pfeiffer[2] proposes a strategy to obtain a proper orientation and placement of the hand so that fingers can reach their commanded contact points without penetration or interaction with the object. His method comprises four basic steps in order to first reduce the number of degrees of freedom between hand and object and then finely optimise the position of the hand:

(i) *Definition of grasp triangle.* They assume grasping with three fingers and regrasping with four fingers. Once the contact points are determined (in a previous grasp synthesis phase), a triangle is defined as shown in Figure 9. Q and R are the points that form the shorter side of the triangle. The center of the grasp is defined as the point halfway between E and the midpoint of $\overline{QR}$. According to this, the grasp frame is defined as follows: x points towards point E; z is normal to the grasp plane; and y is binormal to x and z.

(ii) *Rough hand orientation.* The six degrees of freedom of the object with respect to the hand are reduced by orientating the hand so that it is parallel to the grasp plane. Distance between hand and grasp plane and rotation around z are the remaining *dof.*

(iii) *Finger assignment.* The previous step can result in two symmetric hand orientations with respect to the grasp plane. The selection between these two alternatives is done according to the desired wrench, see section 3.2. The assignment of fingers is done according to the kinematics of the hand. The hand designed at the Institut für Mechatroniks follows the adduction-abduction type presented in the previous section and the thumb is located opposite to the other three fingers. The point E is assigned to the thumb while the points Q and R are assigned to the outer fingers.

(iv) *Optimization of orientation and hand distance.* This step is performed according to a penalty function, ϕ, that ensures that a maximum range of movement is left for each finger. The penalty function is defined as follows:

$$\phi = \sum_i k_i D_i^3 \tag{13}$$

where k_i is a penalty factor and D_i is a function of the finger position:

$$D_i = \begin{cases} \gamma_i - \gamma_{l_i} & \dot{\gamma}_i > 0 \\ \gamma_{u_i} - \gamma_i & \dot{\gamma}_i < 0 \\ \left|\gamma_i - \tfrac{1}{2}(\gamma_{u_i} - \gamma_{l_i})\right| & \dot{\gamma}_i = 0 \end{cases} \tag{14}$$

Depending upon the direction of motion provided by the velocity $\dot{\gamma}_i$ of every joint, the penalty factor is computed by obtaining the difference between actual position and lower and upper joint rotation limits, γ_{l_i} and γ_{u_i}, respectively. When current velocity is zero, the penalty factor measures the distance from current position to the angle halfway between angle limits, i.e. $\gamma_i - \frac{1}{2}(\gamma_{u_i} - \gamma_{l_i})$

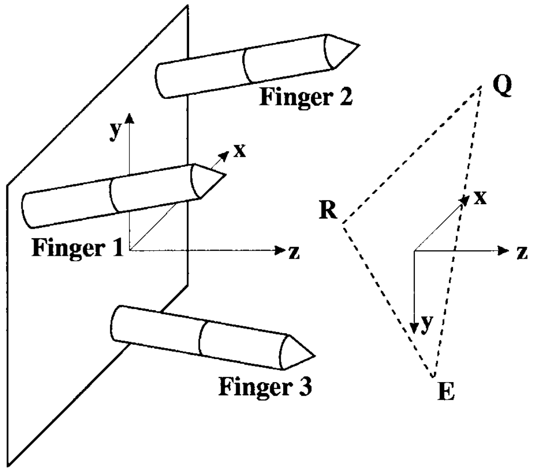


Fig. 9. Rough hand orientation.

3.2 Grasp Synthesis

Grasping is defined by Coelho as a sequence of complex operations ranging from object identification to finding contact points and finally positioning the finger.[37] This is a quite wide definition of grasping and comprises also the previous step, i.e. hand preshaping. Grasp synthesis could be understood as the process of finding contact points and forces so that the wrench required by a task, i.e. forces and moments, can be accomplished.

In general, three different approaches to the grasp synthesis are found in the literature according to the classification given by Coelho, namely geometric grasp synthesis, optimisation-based grasp synthesis and; taxonomy-based grasp synthesis. An inherent characteristic of geometric and optimisation approaches to grasp synthesis is the use of metrics to evaluate the best grasp configuration. Grasp configurations have been described by a variety of analytical measures. Before going to the analysis of grasp metrics it is convenient to have a look at the physics of grasping. We follow here the approach taken by Mason and Salisbury[6] by using the screw representation.

The infinitesimal motion of a rigid body can always be represented by a line along which it translates and rotates. This line corresponds to the *twist* axis of the body. This motion is called a twist and is defined by a six-component vector of twist coordinates, $\underline{t} = \{T_1, T_2, T_3, T_4, T_5, T_6\}$. The first three components of $\underline{t}$ represent the instantaneous angular velocity of the body, $\underline{\omega}$ and the last three components represent its velocity $\underline{v}$.

Similarly the resultant state of forces and moments applied to a rigid body is defined in screw representation by a *wrench*. Again, the wrench can be identified by a six-component vector of wrench coordinates, $\underline{w} = \{W_1, W_2, W_3, W_4, W_5, W_6\}$, where the first three components correspond to the vector of net forces, $\underline{f}$, and the last three components is the net moment, $\underline{m}$.

Two different screws $\underline{s}_1 = \{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6\}$ and $s_2 = \{\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6\}$ are said to be *reciprocal* if the following condition holds:

$$\alpha_1\beta_4 + \alpha_2\beta_5 + \alpha_3\beta_6 + \alpha_4\beta_1 + \alpha_5\beta_2 + \alpha_6\beta_3 = 0 \qquad (15)$$

A screw system, S_1, is reciprocal to a second screw system S_2, if every screw in S_1 is reciprocal to every screw in S_2. The concept of reciprocity applied to the case of wrenches and twists has a physical interpretation: a wrench applied to a body and the corresponding twist are reciprocal when the rate of work is null, i.e. $\underline{fv} + \underline{m\omega} = 0$. With this in mind, it is possible to study the effect of basic contact configuration on the wrench system applied to a body and the twist system left. Mason and Salisbury give a comprehensive description of contacts by using screw representation. Among all types of contact described by Mason and Salisbury, the most interesting concept is that of “Soft finger”.

“Soft finger” is a type of contact that imposes a wrench 4-system. This contact is able to resist forces in all three directions plus torque about the axis of the finger. Therefore, a twist 2-system is left that comprises rotations about two axes tangent to the object surface. Combining the effect of different contact type, and by using the screw representation, it is possible to study the effect of contact groups (grasps) on the motion of the object. The study of contact groups can be made under two different points of view.

(i) *Motion point of view.* When a contact is applied to an object, the available motion of the object is restricted to a given twist system according to the classification presented by Mason and Salisbury.[6] When several contacts are applied simultaneously, the global twist system of the grasped object is the intersection of individual twist systems corresponding to individual contacts. If the resulting global twist system is empty, the motion of the object is completely constrained.

(ii) *Force point of view.* Similarly, every contact results in a set of wrenches exerted on the object. In order to completely restrain the motion of the object an arbitrary external wrench, $\underline{w}$, must be compensated by the grasp wrench system. This condition is expressed by equation 16:

$$\underline{w} = [\underline{w}_1, \underline{w}_2, \ldots, \underline{w}_n]\underline{c} \qquad (16)$$

where n is the number of contact wrenches, $\underline{w}_i$ is the set of wrenches exerted by the contact points, and $\underline{c}$ is a vector of n coefficients.

3.2.1 Grasp synthesis: related concepts.

We have just given the condition for completely constraining the motion of a grasped object. However, it is implicitly assumed that all wrenches can be applied in positive and negative directions, i.e. the coefficients $\underline{c}$ of the linear combination of contact wrenches in equation 16 will, in general, be either positive or negative.

When talking about grasping an object, wrenches cannot be applied in all directions. Frictional wrenches depend on the positive value of normal forces and therefore the contact must be assured during the grasping process. If the coefficients in $\underline{c}$ corresponding to normal forces are negative the grasp will not be stable. *Contact stability* is therefore defined[38] as the ability to maintain the contact state between the fingertips and the object when the object is perturbed by an arbitrary disturbance wrench.

Even when the grasp wrench comprises this “unisense” forces, the grasp can still immobilise the object if the external disturbances act to maintain the contact between fingers and object. This condition is known as *Force Closure* and was first introduced by Reuleaux.[39] A more stringent definition of grasp stability is that of *Form Closure:* the set of grasp wrenches can resist any arbitrary external disturbance. The form closure condition is also known as *complete restraint* and can be analyzed as a function of the grasp wrench system.[6]

Let’s construct the $6 \times n$ matrix W of wrenches, $W = [\underline{w}_1, \underline{w}_2, \ldots, \underline{w}_p, \ldots, \underline{w}_{p+1}, \ldots, \underline{w}_n]$ where the first p columns represent all unisense wrenches. For the grasp to be able of resisting an arbitrary external wrench $\underline{w}$ the following condition has to be met:

$$\underline{c} = W^{-1}\underline{w} \quad \text{with} \quad c_1, \ldots, c_p > 0 \qquad (17)$$

In general, the solution given by equation 17 will comprise both positive and negative values for the first p components of $\underline{c}$. However, for the case where $n \geq 7$ the solution of equation 17 can be written:

$$\underline{c} = \underline{c}_p + \lambda_1 \underline{c}_{h1} + \ldots + \lambda_{n-6} \underline{c}_{hn-6} \qquad (18)$$

where $\underline{c}_p$ is a particular solution and $\lambda_1 \underline{c}_{h1} + \ldots + \lambda_{n-6} \underline{c}_{hn-6}$ is a linear combination of homogeneous solutions.

If the first p components of the linear combination of homogeneous solutions can be made positive by properly choosing the value of coefficients λ_i then they can be easily scaled to obtain a positive vector $\underline{c}$ (at least in its first p components). Therefore the homogeneous solutions can be thought as a bias force, that, without disturbing the equilibrium of the system, can be used to increase contact forces until they are positive. The λ_i are free variables determining the magnitude of the *internal force*. Internal forces, as defined by Cutkosky, are homogeneous solutions of the object equilibrium equations that can be varied to accommodate unisense forces without disturbing the equilibrium.

3.2.2 Optimization-based group synthesis.

The problem of finding a stable distribution of forces to construct a grasp is somehow similar to the problem of finding an adequate force distribution in the links of closed linkage mechanisms. In general, a function of this force distribution is minimized subjected to some equality and inequality constraints, therefore linear and non-linear programming techniques are proper methods to solve the problem.

Associated to the grasp, a quality measure function or metric has to be defined together with appropriate constraints. The usual method of approaching the solution of the force distribution problem,[2,38,40] makes the following assumptions:

(i) Contact between finger and object can be modelled according to a point contact with friction.

(ii) The geometry of the objects can be analytically described according to equations of the kind of equation 19:

$$S(p_{xi}, p_{yi}, p_{zi}) = 0 \tag{19}$$

where $S(p_{xi}, p_{yi}, p_{zi})$ is a spatially differentiable function at the contact points and thus the unit normal vector at the contact point can be derived according to equation 20:

$$\vec{n}_i = \frac{\text{grad } S(p_i)}{\|\text{grad } S(p_i)\|} \tag{20}$$

(iii) Friction cones are often simplified by considering friction pyramids. The approach consist in substituting the general expression of the friction constraint, which is highly non-linear:

$$\vec{f}_t \le \mu \vec{f}_n \tag{21}$$

by the following set of linear expressions:

$$\left.\begin{array}{l} \vec{f}_{tx} \le \mu \vec{f}_n \\ \vec{f}_{ty} \le \mu \vec{f}_n \end{array}\right\} \tag{22}$$

where $\vec{f}_t$ is the tangential component of the contact force which can be decomposed in $\vec{f}_{tx}$ and $\vec{f}_{ty}$, $\vec{f}_n$ is its normal component and μ is the friction coefficient.

Several different metrics have been used in the literature:

Capacity to resisting external disturbances. This metric was introduced by Guo[35] when studying the asymptotical stability of the grasp. He derived a linearized version of the small vibration equation of the grasping system, see Eq. 23, by using Lagrangian formulation.

$$M\delta\ddot{x} + B\delta\dot{x} + K\delta x = 0 \tag{23}$$

Because of the small vibration assumption made by *Guo*, matrices B and K depend only on the *Grasping State Matrix*, $G = [p_1, \ldots, p_k] \in \mathrm{R}^{3\times k}$, where p_i is the position vector from the mass center of the object to the ith contact point. The characteristic equation of the linear system given by Eq. 23, is:

$$\Psi(\lambda, G) = \det[\lambda^2 M + \lambda B + K] = 0 \tag{24}$$

Since the system is supposed to be lightly damped the roots of the system are:

$$\left\{\begin{array}{l} \lambda_{2j-1} = -r_j + \omega_j i \\ \lambda_{2j} = -r_j - \omega_j i \end{array}\right. \quad j = 1, 2, \ldots, 6 \tag{25}$$

and the time constants of the vibrating system can be given by:

$$T_j = -\frac{2}{(\lambda_{2j-1} + \lambda_{2j})} \quad j = 1, 2, \ldots, 6 \tag{26}$$

The asymptotical stability is ensured by defining the maximum time constant as a quality measure of the grasping system:

$$\min_G \{T_{\max}(G)\} = \min_G \{\max[T_1, \ldots, T_6]\} \tag{27}$$

The metric presented by Guo ensures a rapid decay of vibrations since the smaller the time constant of the grasping system the more rapid the decay of vibrations. The metric that measures the capacity to resisting external disturbances is optimised by using a conjugate direction descend method with a linear search by the golden section method. The constraints to the problem were in this case, the position of grasping point on the surface of the object, given by Eq. 19, the condition of normal positive forces at the contact points, i.e. $\vec{n}\vec{f} \ge 0$, the condition of fingertip forces on or inside the friction cone, i.e. $\vec{n}\vec{f} \ge |\vec{f}_t|$ (note that this second condition, $\vec{n}\vec{f} \ge |\vec{f}_t|$, is more stringent than the previous one, $\vec{n}\vec{f} \ge 0$, and thus the latter is comprised in the former), and finally the condition of stable grasp given by the positive definiteness of the grasping stiffness matrix.[6]

Finger interaction forces. The concept of finger interaction forces was introduced by Kumar.[40] An interaction force is defined as the component of the vector difference of the finger contact forces at any two fingers along the line joining the two contact points. The idea behind the work of Kumar is to overcome the problems of linear and non-linear programming techniques to solve optimisation problems in terms of computational time. To achieve this goal he relies on sub-optimal optimization techniques.

The approach to obtain the grasping forces comprises two steps, namely, (a) Determination of the forces required to maintain the equilibrium of the grasped object assuming that interaction forces are zero, and; (b) determination of the interaction forces needed to produce the finger forces computed in step (a) without the friction angle constraint.

The proposed method is optimal to the extent that every component, i.e. equilibrating and interaction forces are independently optimised. The method moreover assumes that contact normals are along the lines joining contact points to the centroid of these points. Better results are of course obtained if a global minimization of the maximum net finger contact force is carried out; however, computational efficiency of this method is an advantage.

Minimum difference of the finger force magnitudes. A number of metrics to define the optimum grasp where investigated by Wölfl[41] and Pfeiffer[2] i.e. minium dependence on the friction coefficients, minimum tangential finger forces, minimum sum of all finger force magnitudes, minimum of the maximal finger force and minimum difference of the finger force magnitudes. Among all these metrics, Wölfl and Pfeiffer report that the last approach gives the best distribution of forces over all fingers.

The condition of minimum difference of finger forces can be stated according to the metric G given by Eq. 28:

$$\min_G = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ (j\ne i)}}^{n} (|f_i|^2 - |f_j|^2)^2 \Rightarrow \min \tag{28}$$

The approach followed by Wölfl and Pfeiffer proposes a novel decomposition of contact forces. All the previous works rely on a decomposition based on manipulation forces and internal forces. Internal forces were already defined in a previous section. Manipulation forces were introduced by Yoshikawa and Nagai,[42] and are defined as the forces which generate the required external wrenches on the object.

Wölfl and Pfeiffer propose a decomposition based on normal and tangential directions to the contact point. Again they rely on an exact analytical description of the object geometry and assume frictional point contact between object and fingertips. The assumption of point contact can be considered accurate when the dimensions of the fingertips are small enough.

When considering geometrical constraints as those described by Eq. 19, it is possible to work out the same constraint in polar co-ordinates by considering the following relationship between Cartesian coordinates and polar coordinates:

$$\begin{cases} p_{xi} = r(\zeta,\ \xi)\cos\zeta\sin\xi \\ p_{yi} = r(\zeta,\ \xi)\sin\zeta\cos\xi \\ p_{zi} = r(\zeta,\ \xi)\sin\xi \end{cases} \tag{29}$$

Substituting Eq. 29 into Eq. 19 it is possible to compute numerically $r(\zeta,\ \xi)$, so that contact points are located on the object surface. The optimization criterion given in Eq. 28 is subject to the following constraints:

(i) Force and moment equilibria. If f_{ni} and f_{ti} are normal and tangential forces at contact points and F_e and M_e are the desired external force and moment, force and moment equilibria require:

$$\sum_{i=1}^{n} (f_{ni} + f_{ti}) - F_e = 0 \tag{30}$$

and

$$\sum_{i=1}^{n} r_i \times (f_{ni} + f_{ti}) - M_e = 0 \tag{31}$$

(ii) Contact and friction cone constraints require unisense condition for normal forces and tangential forces inside or on the friction cone.

(iii) The above conditions ensure equilibrium and avoid slipping between object and fingers. To ensure stability another constraint is imposed based on the fact that the smaller the sum of normal vectors at contact points the more stable the grasp is:

$$\left|\sum_{i=1}^{n} n_i\right| \leq S \tag{32}$$

where S is a desired stability measure.

(iv) The separation constraint guarantees that the resulting contact points are not too close to one another:

$$|r_i - r_j| - \epsilon_{\min} \geq 0 \tag{33}$$

where ε_{min} is the minimum required separation between contact points.

The number of parameters to optimise is 5 × n where n is the number of fingers grasping the object. The optimisation is carried out using successive quadratic programming procedures.

3.2.3 Grasp synthesis by control composition. All previous approaches to grasp synthesis rely on off-line computed grasp metrics that do not allow for differentiability and, as a consequence, it is not possible to construct control surfaces to establish a control approach to the grasp synthesis problem. Moreover, previously computed metrics are computationally expensive and involve optimisation techniques that do not allow directional information to guide a grasp controller.

A novel approach based on control composition is presented by Coelho and Grupen.[37] Control composition schemes are commonly applied to complex control task and are based on a decomposition of control tasks into subtasks. Behaviours are then assigned to every subtask, and eventually individual behaviours are composed to form a composite controller capable of solving a family of specific control tasks.[37]

Individual controllers are based on metrics that are being maximised during the grasp synthesis. In their work, Coelho and Grupen made a decomposition of the overall grasp synthesis controller into two individual controllers, namely, (a) a force closure controller, and; (b) a moment closure controller.

In order to realise their controller, two basic assumptions were made: (a) contacts are modelled as frictionless point contacts, and; (b) Forces and moments are considered unitary and thus a scaling of the geometry of grasped object is done; as a consequence, the solution grasp is optimised based on shape rather than on dimension.

The same metric is used to develop both controllers, the *Stable Grasp Sufficiency Metric*. The new metric is developed from the residual wrench vector, $\vec{\rho}$:

$$\epsilon = \vec{\rho}^T \vec{\rho} = \left(\vec{t} - \frac{1}{n}\sum_{i=1}^{n} \hat{\omega}_i\right)^T \left(\vec{t} - \frac{1}{n}\sum_{i=1}^{n} \hat{\omega}_i\right) \tag{34}$$

where, $\vec{\rho}$ is the net wrench over n contacts, $\hat{\omega}_i$ is the wrench vector resulting from the ith contact point and $\vec{t}$ is an optional wrench closure bias.

The above general stable grasp sufficiency metric is then particularised for the force controller and the moment controller. In order to do so, the object geometry is modelled according to a Gaussian sphere. Accordingly, the wrench of a frictionless point contact, $\vec{\omega}(\theta,\ \phi) = [f_x, f_y, f_z, m_x, m_y, m_z]$ is for the force closure controller:

$$\begin{aligned} &[f_x, f_y, f_z, m_x, m_y, m_z] \\ &= [-\cos\theta\cos\phi,\ -\sin\theta\cos\phi,\ -\sin\phi,\ 0,\ 0,\ 0] \end{aligned} \tag{35}$$

and

$$\epsilon_{FC} = \left[t_{fx} - \frac{1}{n} \sum_{i=1}^{n} \cos\theta \cos\phi \right]^2 + \left[t_{fy} - \frac{1}{n} \sum_{i=1}^{n} \sin\theta \cos\phi \right]^2 + \left[t_{fz} - \frac{1}{n} \sum_{i=1}^{n} \sin\phi \right]^2 \qquad (36)$$

Similar equations are obtained for the moment closure controller, ϵ_{MC}. Control composition from these two individual controllers is performed according to knowledge-based heuristic composition and learning-derived composition and an on-line grasp synthesis controller is obtained.

4. CONCLUSIONS

Kinematics of dextrous multifingered hands is a well studied matter and a number of indices measuring different kinematical aspects of the design have been proposed. However, when considering dextrous hand design, actuation technologies are still a major impediment for obtaining compact and reliable solutions. Currently existing prototypes rely widely on electrohydraulic actuators even when present trends point at non-traditional actuation technologies based on shape memory alloys or contractile polymers as promising alternatives. These high power density driving technologies are especially interesting in those applications where space and weight are at a premium, i.e. prosthetics.

The slow development in actuation technologies made the designers place actuators somewhere behind the wrist and thus transmission to the joints has become a major issue. This is usually solved by using redundant tendinous systems that provide low inertia compliant transmission. When actuation technologies are improved, transmission systems will become a second order problem.

Control of dextrous multifingered hands comprises several partial tasks. Within this work they have been classified according to grasp preshaping operations and grasp synthesis. Grasp preshaping is a task oriented operation aimed at reducing the number of degrees of freedom between hand and object to be grasped. On the other hand, grasp synthesis comprises the determination of a grasp under the condition of stability, equilibrium and dexterity. Grasp synthesis is commonly approached either by optimization based processes or by control composition.

Optimization based approaches are computed off-line by defining objective functions subjected to constraints. Usually these optimisation-based approaches do not allow for online controllability since used metrics do not permit the construction of control surfaces. A possible solution comes from control composition approaches even when considering advanced autonomous operation with dextrous hands; it seems some realisation based on sensor guided manipulation is still required.

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