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GRASPING AND CONTROL ISSUES IN ADAPTIVE END EFFECTORS

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ABSTRACT

Research into robotic grasping and manipulation has led to the development of a large number of tendon based end effectors. Many are, however, developed as a research tool, which are limited in application to the laboratory environment. The main reason being that the designs requiring a large number of actuators to be controlled. Due to the space and safety requirements, very few have been developed and commissioned for industrial applications. This paper presents design of a rigid link finger operated by a minimum number of actuators, which may be suitable for a number of adaptive end effectors. The adaptive nature built into the end effector (due to limited number of actuators) presents considerable problems in grasping and control. The paper discusses the issues associated with such designs. The research can be applicable to any adaptive end effectors that are controlled by limited number of actuators and evaluates their suitability in industrial environments.

Keywords: End Effectors, Finger Design, Robotic Hand, Adaptive Finger, Robotic grasping

INTRODUCTION

Efforts are being made world wide to remove human operators from hazardous environments. Such environments include, space exploration, underwater mining, and operations in nuclear and chemical industries. The objective is to reduce or remove the risk from the operators. In order to achieve this one has to rely on robotic or autonomous systems that have robust and flexible mechanical structure to adapt to the environment's needs. However, the current level of technology does not provide off-the-shelf solutions for every possible situation because such environments are unknown and there is a degree of uncertainty involved. The existing systems can meet the needs that are well defined and known in advance, but if the operations are to be performed autonomously in such environments the unstructured and non-deterministic nature of the environment precludes all this. This requires special purpose system to be developed, which may put stringent specification on the material and components of the robotic systems.

The robotic system required to operate in such environment should be versatile enough to handle unknown objects and situations i.e. the gripper of the robotic system should be able to grasp objects of different shapes and mass more like the human hand than a conventional robotic end effector. The design considered in this paper has evolved from an industrial need for a tele-operated system to be used in

nuclear environments. The end effector is designed to assist repair work in nuclear reactors during retrieval operation, particularly for the purpose of grasping objects of various shape, size and mass.

THE TARGET END EFFECTOR

The development of the end effector is based on the design study carried out for an in-reactor manipulator [1]. Specifications of the end effector were developed for the Central Electricity Generating Board (now Nuclear Electric plc. UK), as a part of the Magnox reactor repair program. The design concept was such that the system was as flexible/dexterous as possible - "very user specific" is true as CEGB defined the design - but in practice the specification is highly generic. The design was developed to produce an adaptive end effector capable of handling most general type of objects during debris retrieval. Environment inside the reactor is unstructured by its very nature where objects of different shapes, sizes and mass are available. The retrieval operation does not require manipulative functions nor any tool holding facilities, only versatile grasping capability of the end effector is of paramount importance. The key specifications of the end effector are:

- The end effector to have three fully articulated fingers typically arranged symmetrically. The fingers should be capable of handling unusually shaped objects.
- The end effector should be capable of gripping a variety of objects for example, M6 to M30 nuts, 6 to 50 mm diameter bars up to 150 mm long picking them from a flat surface, 50 mm cube, 100 mm diameter, 6 mm thick disc from a flat surface.
- The maximum gripping force should be 100 N for a 100 mm diameter disc.
- The maximum overall diameter of the end effector is to be 120 mm, should weigh less than 5 kg and should be as compact as possible.
- A closure time of 2 to 5 seconds needs to be achieved.
- Each finger should be capable of independent control.
- A range of sensors needs to be incorporated in the end effector.
- The unit is to be manufactured from stainless or low carbon steel and the structure should be capable of absorbing forces of the order of 500 N due to collision.

DESIGN RATIONALE

Based on the above specifications it is clear that the end effector should have versatile grasping options for precision and power grasps [2] and the design should be mechanically robust and structurally flexible. This further requires that the end effector uses minimum number of actuators and the motion is transmitted via rigid links for space and safety reasons forming adaptive and compact unit.

Over the last thirty years a considerable number of dexterous end effectors have been developed. The most notably being the Stanford/JPL [3] and Utah/MIT hands [4], which were developed for research into object manipulation. These designs were based on the fingers being actuated via tendons

from an external actuator pack. The Belgrade/USC hand [5] was developed with prosthetic application in mind, and has a more compact actuating mechanism. Okada [6] designed a three-fingered hand with 11 degrees of freedom using pulley/tendon system to perform assembly operations. A three-fingered hand developed at the University of Pennsylvania [7] and is commercially available as BarrettHand has a compact design; however, the hand uses four actuators on a worm drive with cable and breakaway clutch to provide finger motions. Some end effectors developed with industrial application in mind include the Karlsruhe hand [8], and Delft University of Technology hand [9] and the dexterous reconfigurable system for packaging [10].

Many dexterous hand designs are tendon based, where each finger joint is connected to a remote actuator by a flexible cord or tendon. To achieve full joint motion a minimum of two tendons are required per joint. The advantage of this approach is that the actuators are remote from the hand and hence reducing the overall inertia by removing mass from the end of the manipulator. If size is not a limitation, the actuators can be mounted external to the hand, with the power transmission to the hand via tendons. While satisfactory for experimental systems, this approach is not suitable for industrial applications. The space restriction imposed by certain industrial applications result in the external actuators together with tendons not being a practical design proposition. In addition, the use of hand mounted pneumatic and hydraulic actuators in many applications are considered to be impractical, due to leakage problems. The design of the hand and finger are to a large extent dictated by the approach taken to transmit the actuator forces to the finger joint. If special purpose localized actuators, such as artificial muscles [11] are excluded, only two realistic approaches for power transmission within the hand between the finger-joints and actuators need to be considered; tendons or a rigid link kinematic chain.

In a number of applications for a fully dexterous hand to operate satisfactorily, electric actuators need to be located within the profile of the end effector. As physical size of the system limits the number of actuators, the design solution presented requires the motion of the fingers to be controlled by solid mechanical linkages. An advantage of this design is the high reliability of electric motors; this was an important consideration as the manipulator is intended for continuous industrial operation.

The finger mechanism presented in this paper originated from the design developed for the University of Southampton Whole Arm Manipulator (WAM) [12]. This manipulator was developed for insertion into the human sized rubber glove for use in a conventional glove box. Due to the design requirement, this manipulator has an anthropomorphic end effector with four adaptive fingers and a prehensile thumb, the grasp being controlled by three motor-gearboxes assemblies located within the palm, with connections to the finger segments via solids mechanical linkages.

THE ADAPTIVE FINGER

The design of the finger mechanism considered in this paper has been fully described in our previous paper [13] but is being outlined here to present the issues associated with grasping and control. The finger consists of three sections (lower, middle and tip) pivoted together as shown in Fig. 1,

with the maximum relative movements of 90° between each sections. The upper two finger sections are used to produce a co-ordinated curling motion. The tip is linked to the lower section by link 2, so that any motion of the middle section by link 1 will cause the tip to move, producing curling motion to the finger. The lower and middle sections are individually connected to the actuating mechanism at points B and K. The mechanism is grounded at joints A and J.

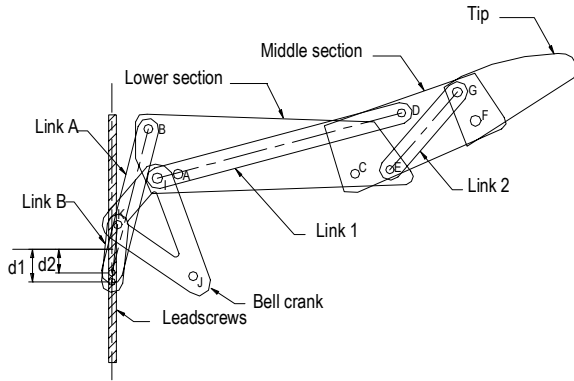


Fig. 1. Basic Finger Mechanism

The finger mechanism can be considered to have two degrees of freedom:

- *Bending*, where displacement of joint B bends all the three finger segments about joint A.
- *Curling*, where displacement of joint K results in the curling of the two upper finger segments about joint C.

For adaptive mode of grasping the finger is first bent towards the object. After the first finger-section has made contact the 'bend' component of the motion is impeded and the actuator effort is directed towards the 'curl' component of the motion. This way all three finger-sections can make contact with the object and adapt to an optimum grasp configuration, as shown in Fig. 2 (stepwise).

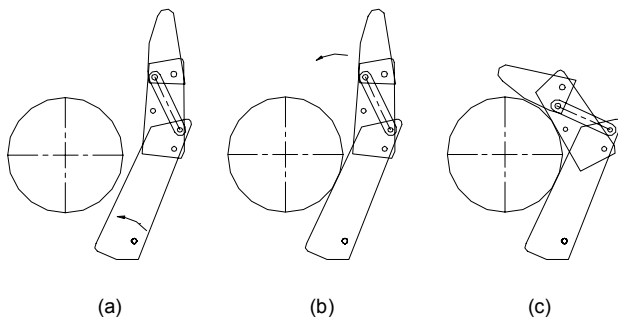


Fig. 2. The adaptive grasping

Thus the finger requires two input drives. This can be produced in a number of ways, depending on the application requirements. Three approaches can be considered to drive the finger:

- Equalizing mechanism.
- Fully independent drives.
- Differential gearbox.

Equalizing Mechanism

The equalizing bar mechanism used in the end effector of the Whole Arm Manipulator is shown in Fig. 3. In the rest position the finger is considered to be in the fully extended position. To close the finger the equalizer bar is driven to the left, by a crank and slider mechanism. Due to the built-in difference in the mechanical advantages between links A and B and their respective sections, the finger is designed to preferentially rotate around pivot A of the lower section. The design of the mechanism is such that the finger will remain straight while it rotates around this pivot. The rotation of the complete finger will continue until such time as the lower section is stopped either at its mechanical limit or by an external object.

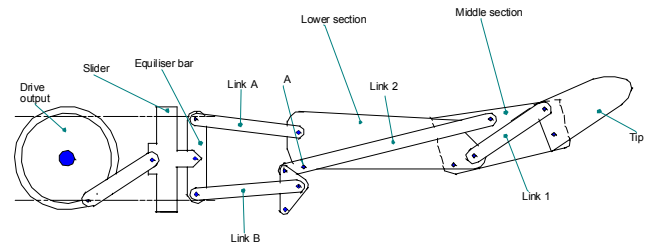


Fig. 3. Equalizing bar mechanism

As the lower section and link A cannot move, force is transferred to the middle section, via link B, thus causing the upper two sections of the finger to curl over and complete the grip around the object. The resultant finger motion is similar to that of a human finger and is described as being "tip driven", as the fingertip effectively leads the motion. The position of the equalizing bar is controlled by the loads applied to the finger section thus is considered to be indeterminate. While compact, the design relies on external forces provided in the WAM application by the rubber glove, which is used to stabilize the finger position. The WAM design rationale was dictated by the tight size constraint of the hand, its enclosing glove and the operating environment. The WAM hand is capable of forming a range of grasps, which allowed it to perform a wide range of handling operations [14]. However, due to the design of the finger mechanism, the movement of its fingers cannot be precisely controlled during grasping operation, as this is determined by the compliance of the glove.

Fully Independent Drives

Here the two motions are independently powered and controlled. This requires two motors within the end effector envelope for each finger. If, however, the finger is to be rotated about its own axis to produce three dimensional capabilities, an additional motor is required. This approach does allow fully

controlled independent motion to be achieved, however at the expense of additional cabling and possible size restrictions.

Differential Gearbox

As discussed, to satisfactorily control the finger both input links need to be individually controlled. However, this will require two actuators to be controlled thus has space and safety implications. Due to application constraints imposed, only a single motor could be used to control all the required motions. This requirement led to the development of a mechanism capable of independently controlling the two input links.

The design of the actuating mechanism is shown in Fig. 4. The actuating mechanism has a central differential gearbox driving two lead screws supported on a rotary frame. The motor connected to the differential gearbox can be used to drive the two lead screws as well as the mechanism frame, providing three different components of a motion from a single motor. These motions are determined by the use of three electromagnetic brakes.

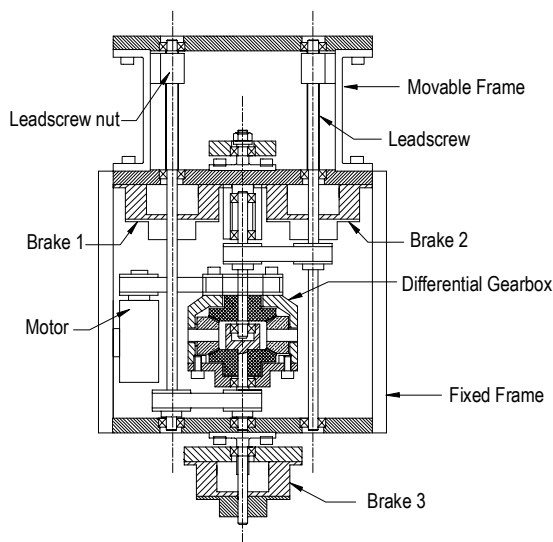


Fig. 4. The differential finger drive mechanism

As shown in the figure brakes 1 and 2 control the two lead screws, while brake 3 controls the finger orientation relative to the end effector frame. Thus the mechanism can provide three degrees of freedom to the finger. The structure of the finger offers independent curl motion while the bend motion is only partially independent as this results in a slight curling effect to the finger. By controlling the three brakes the three components of motions can be controlled individually or in combination, thus the finger can be operated either in adaptive or precise control mode with concentric or opposing-thumb configuration [15]. The presented design is compact and as per the end effector specification, however, this has some implications in grasping and control as discussed in the following sections.

FINGER CAPABILITY

A prototype finger mechanism based on the differential gearbox has been built to evaluate the performance of the system [13]. This is the mechanism used for controlling the

adaptive finger and the presented grasping and control issues relate to this design. The mechanism uses ball leadscrew with high lead (2 cm) to enable bi-directional motion transmission. The fingers of the end effector are fixed symmetrically at 120° spacing on a circular base giving a high degree of flexibility in gripping objects. The structure of the finger allows bending and curling action to take place in a plane. The flexibility of the hand is enhanced by the capability of the fingers to rotate about their axes allowing generation of either two or three fingered parallel grips, or three fingered pinch grips [16]. The basic construction of the finger is based on an open structure using side plates and cross pivots. This mode of construction gives the maximum clear space within the profile of finger for accommodating the mechanical linkages and for incorporating sensors. As nine degrees of freedom result from the design, a large number of precision and power grips can be produced.

Since the fingers form planar mechanism and capable of rotating about their own axis, it is important to trace the loci of the finger to specify the workspace of the end effector. Initially the fingers are considered to be aligned horizontal, parallel to the base plate of the end effector. In this situation there are no bend and curl in the finger and both leadscrews are at minimum displacements (d_1, d_2) of 0.006 m (Fig. 1). This corresponds to the fingertip having a maximum X component and minimum Y component as shown in Fig. 5. The other three combinations of the limits of the leadscrews are shown by the starred points in the figure. Between these limits the finger can adopt to any combinations of curl and bend depending on the leadscrews displacement. The zero on X-axis indicates the finger origin and X, Y coordinate represents the fingertip locations. It can be seen from the figure that the fingertips can be located 0.1 m away from the origin at a vertical distance of 0.14 m. Thus the end effector is capable of gripping objects of up to 200 mm diameter which is more than the requirement laid out in the specifications. Also the finger is capable of moving to the left of the origin by 0.05 m at a vertical distance of 0.14 m which means that the finger is capable of gripping as small object as possible, only limited by the width of the fingertips.

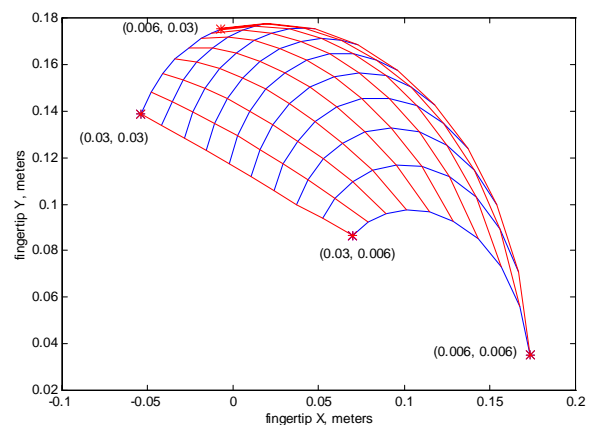


Fig. 5. Fingertip loci with the leadscrews displacement

CONTROL ISSUES

Even though grasping is not an exact science, some sort of pre-planning is required to achieve successful grasping. To grasp an object, the end effector must be positioned and

oriented suitably in relation to the object such that gripping can be possible. If the object is not totally enclosed by the envelope of the fingers and not sufficiently restrained, the effect of the first contact might simply be to move the object. There is also a possibility that fingers can touch the object at points that are not equidistant from the center of the end effector. This situation can arise if the object is of irregular shape or the object is not exactly lying on the central axis of the end effector as shown in Fig. 6. This may result in formation of an unsymmetrical grasp with respect to the points of contact on the grasped object. For the unsymmetrical grasp the centroid of the triangular grasp plane does not lie on the central axis of the end effector which means the grasp is unbalanced with respect to finger position (see the figure). Further due to the complex kinematic chain of the finger, it has been shown that the direction of the fingertip-normals are not co-planar at the plane of contact [17], this will result in force and moment unbalance [18]. The fingers need to move in horizontal and vertical directions co-operatively to minimize this unbalance and in the proposed end effector this has to be achieved by a single motor per finger. Thus it is important to see how the leadscrews displacement changes when the finger has to track a precise path.

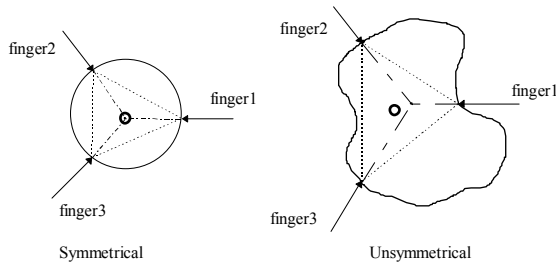


Fig. 6. Position unbalance in grasp formation

From the inverse kinematics analysis [13], the leadscrews displacement can be generated when the fingertip executes straight line motion in vertical as well as in horizontal directions. Such motions may have relevance in object manipulation by the articulated finger. However, here we are investigating how to minimize the grasp unbalance by controlling the finger motion. Fig. 7 shows the leadscrews displacement required for the fingertip tracing a vertical straight line motion from 0.14 m to 0.02 m at a fixed X position of 0.07 m.

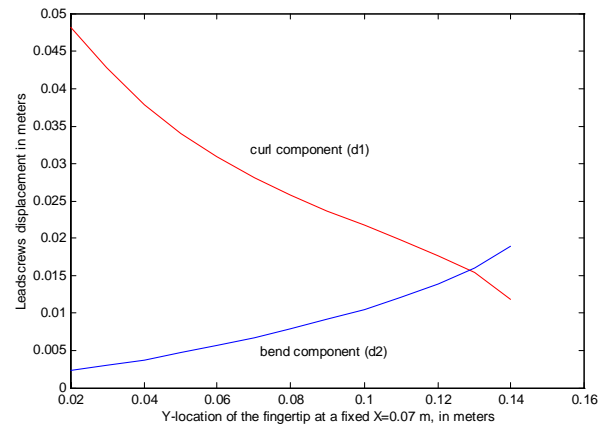


Fig. 7. Leadscrews displacement for vertical motion

The finger motion with respect to the base joint A can be seen in a simple kinematic chain representation in Fig. 8. Throughout the vertical motion it has been found that the leadscrews displacements change in such a way that there is one and only one vertical fingertip position available for a set of d1, d2 displacements. However, the leadscrews displacement is seen to be taking place in opposite direction (Fig. 7). This means that for controlling the motion by a single motor using the differential unit, the motor has to change the direction of rotation for each individual leadscrew in succession. Due to the backlash in the system linear motion cannot be achieved and the accurate position control in vertical direction is difficult.

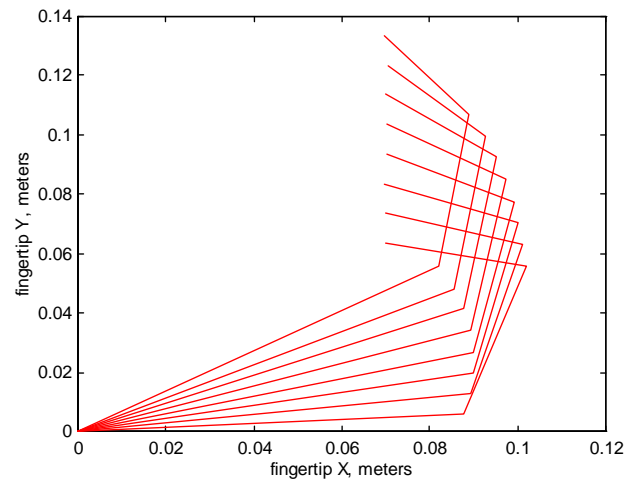


Fig. 8. Simulated vertical motion of the fingertip

While the finger is tracking a horizontal straight line the leadscrews displacements are as shown in Fig. 9. As a result the position can be better controlled by sequentially operating each leadscrews in succession.

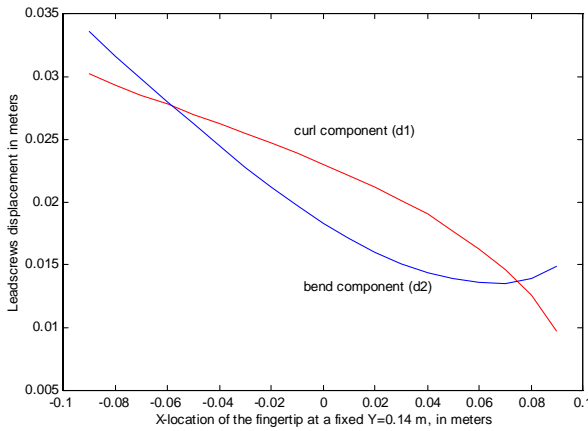


Fig. 9. Leadscrews displacement for horizontal motion

It is important to note here that the unbalance minimization in position can mostly be achieved by horizontal movement of the finger, and fortunately this does not require motion reversal sequence as it was in the previous case. Thus this is an interesting feature of the finger, which makes it more suitable for grasping application than manipulation.

GRASPING ISSUES

One of the most basic and necessary qualities of a grasp is that the grasped object is in equilibrium. A grasp is said to be in equilibrium if the components of forces and moments acting on the grasped object all add up to zero. In case of the object grasped by multifingered end effectors, the equilibrium of grasp requires that no resultant force acts on the object and the object is fully restrained. If the resultant force is not zero, there will be unbalance in force and moment, which will tend to move and rotate the object.

For the present end effector, unbalances in force and moment may arise even at the equal motor torque at each finger due to the unsymmetrical location of fingertips from the central axis of the end effector. This is due to the fact that the structure of the finger offers different contact forces at different locations for the same motor torque [17]. Also the direction of fingertip-normals are different at different fingertip locations, which again results in unbalance in force and moment. Thus in order to achieve equilibrium of the grasped object, these unbalance need to be minimized without slipping the object and satisfying the related constraints.

In order to minimize the system unbalance (position, force and moment), a grasping model of the end effector has been developed which is based on the following assumptions:

- Direction of the fingertip force is same as the normal vector at the contact point, which can be defined from the bend of each finger.
- Fingertips make full contact with the object during grasping and the force at the fingertip can be provided by the attached sensors.
- Frictional forces arising at the fingertips are not considered for the derivation of the equilibrium equations since the

frictional constraints are already met in the fuzzy control implementation [19].

- The mass of the object has not been considered since the fuzzy control applies appropriate torque to hold the object weight.
- Concentric object grasp has been considered in this implementation.
- Equilibrium of the grasped object has been simulated for tip grasp. In the case of wrap around grasp, the object is over-constrained by several contacts, thus only the contact forces need to be controlled to avoid crushing.

The steps involved in grasping by the three fingered end effector starts with fingers allowed to move in the enclosing direction. Each finger motion is impeded as soon as it records a contact event with the object. The fingers under this condition apply a minimum force to the object. At this situation the lift is attempted and the control is passed to the fuzzy logic which generates appropriate motor torque for holding the object [20]. Once the fuzzy control has ensured that the grasped object does not slip, the equilibrium of the grasped object is tested by conducting the position, force and moment unbalance test. If the grasp is unbalanced with respect to any of these parameters, the algorithm attempts to modify the unbalance as far as possible within the allowed constraints. To ensure successful grasping it is necessary to ascertain that each finger touches the object so that sensors can provide the measure of contact force. The sensing and control part of the end effector have been presented in our earlier work [19, 20], here only mechanical aspect of the end effector grasp is considered for unbalance minimization.

From the preceding discussions it is clear that the structure of the finger does not allow the control of the finger motion in a truly three dimensional space. Thus force and moment balance can be achieved by changing the fingertip forces and contact positions over the grasped object. Note that the finger rotation can only be used to change the grasping configurations (from concentric to two fingers and opposing thumb grasp), this motion cannot be used for changing the finger position over the grasped object.

In order to simulate object grasping, the model allows initial position unbalance to be introduced into the system and the algorithm based on least square method attempts to minimize the distance between grasp centroid and the central axis of the end effector. This in actual end effector will be achieved by co-ordinated movement of the three fingers, mostly in horizontal direction, so that object remains in grasp. Fig. 10 shows position unbalance minimization for the case when finger 1 is displaced by 30% inward, finger 2 by 25% outward and finger 3 by 15% inward with respect to the corresponding symmetrical grasp. As seen in the figure the algorithm is able to minimize the unbalance to the extent of 80%.

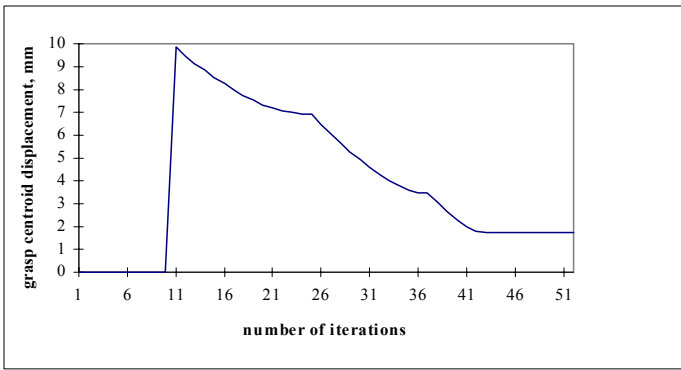


Fig. 10. Position unbalance minimization

While minimizing the position unbalance it is interesting to see from Fig. 11 that the torque required by the motor to drive each fingers is also reduced. The leadscrews displacement during this minimization is shown in Fig. 12. Non-intersecting and identical slopes of the displacement lines suggest that for the position unbalance minimization both the leadscrews of the finger moves in the same direction, thus direction reversal is not required and can balance position as well as fingertip force in one minimization process (Fig. 11). The number of iterations on the axis represents the incremental rate at which the simulation is being carried out.

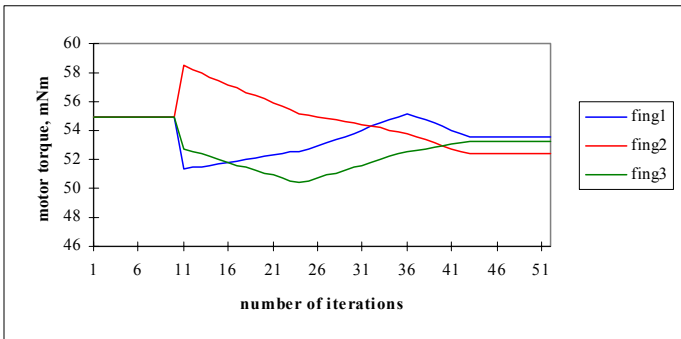


Fig. 11. Torque variation during unbalance minimization

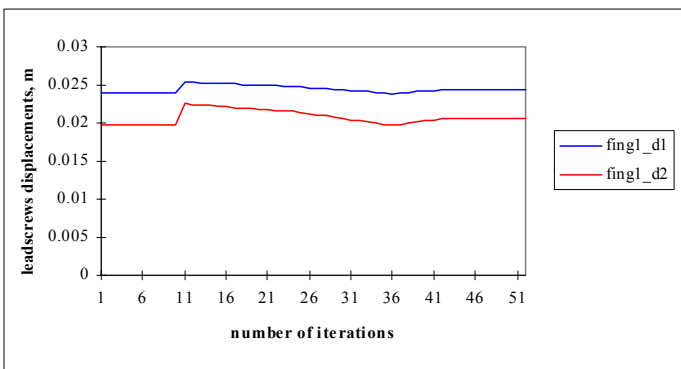


Fig. 12. Leadscrews displacement during minimization

The resulting effect of minimization can be shown in Figs. 13 and 14 where unbalance in force and moment components can be seen to be closing to zero at the end of the process. The fingertip forces considered in the simulation are 3N, 2N and 1N for fingers 1, 2 and 3 respectively with the position unbalance as shown in Fig. 10.

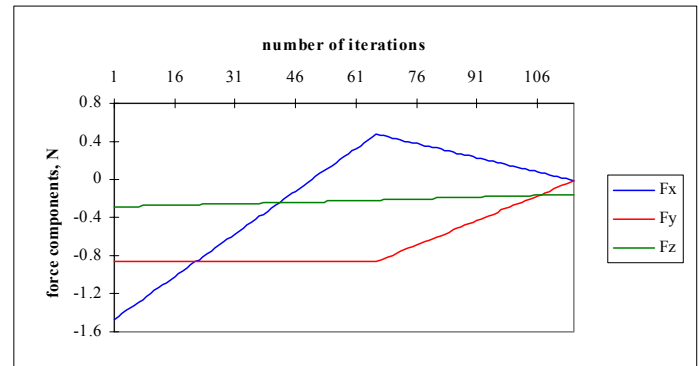


Fig. 13. Minimization of the force components

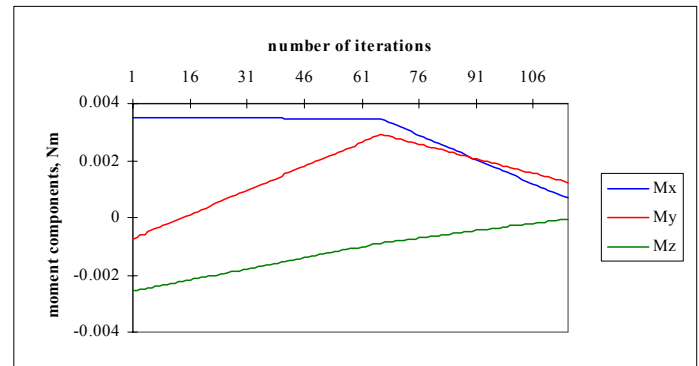


Fig. 14. Minimization of the moment components

CONCLUSIONS AND DISCUSSION

Grasping and control issues of an adaptive end effector have been presented in this paper. As far as the design of the end effector is concerned, the mechanism removes a number of significant problems experienced with tendon-based designs. The finger actuation mechanism forms a compact and positive drive unit within the end effector's body with the use of solid mechanical linkage and the transmission through the toothed belts, thus offering a strong and reliable system for use in industrial environments where safety is an important consideration.

The control of the finger is easier with one motor and three brakes as compared to individually actuated finger joints, since only one motor needs to be controlled together with brakes. The fingers can be driven in adaptive as well as precise control mode which can be rotated about its own axis allowing it to form either concentric or two fingers and opposing thumb grasps. Thus the finger design offers a practical solution to the specific tasks of grasping objects of specified shape and size securely within the structure of the end effector. However, the

finger operation for tracking straight line motions are difficult to achieve due to the coordinated displacement requirement of the leadscrews, as both the leadscrews are operated by a single motor and the motion needs to be transferred from one axis to the other in succession. This suggests that design modification to the finger drive mechanism will be required if the fingers are to track an exact trajectory. A basic mechanical design modification could be to drive each leadscrew by individual motors, however, this will have control implications, since nine motors are to be controlled.

As shown in the paper, it is difficult to attain minimum grasp energy configuration at all positions due to the complex kinematic chain of the articulated finger. Hence a method has been developed to minimize the system unbalance in position, force and moment. The algorithm operates well for various conditions of the fingertip loading. The algorithm is especially valuable in case of finger loading in an unsymmetrical grasp, which is most likely to occur in unstructured environments. The simplicity in implementation of the minimization algorithm is possible due to the structure of the finger, which is not capable of performing motions in full three dimensional space. Consequently, it puts constraints in the force and moment minimization, which is achieved by changing the finger force and by planar movement of the fingertip over the grasped object. Clearly, the end effector is not designed for object manipulation where fine finger motions are required but is developed for grasping and handling operations. However, the end effector can execute limited manipulation during grasping. The fingers are shown to coordinate with each other during position balance exhibiting a condition of simple manipulation with the grasped object. This minimizes the unbalance in grasp which also relieves the motor of drawing extra current. The unbalance minimization algorithm in the actual system will be used as a corrective measure to ensure that none of the fingertip applies excessive force to cause damage to the grasped object and to maintain the condition of equilibrium.

The end effector with three motors forms a compact unit and is capable of grasping objects of various shape, size and mass. Even though the motion is transferred from one leadscrew to the other in succession this does not bring in any significant problems as far as grasping in industrial environment is concerned. The paramount considerations in such environments are ruggedness, reliability and safety of the system, which the presented end effector is able to provide. Thus it can be useful in industrial environments where space and safety is of highest concern.

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REFERENCES

[1] Crowder, R. M., 1990 "Special purpose multifingered robotic end effectors" Proceedings of the American Nuclear

Society 38th conference on remote systems technology, Vol. 2, pp. 52-58.

[2] Cutkosky, M. R., 1989, "On grasp choice grasp models and the design of hands for manufacturing tasks", *IEEE Transactions on Robotics and Automation*, Vol. 5. No 3, pp. 269-279.

[3] Salisbury, J. K. 1985, "Design and control of an articulated hand", In M. T. Mason and J. K. Salisbury edited, *Robot hands and mechanics of manipulation*, MIT Press, Cambridge, MA, pp. 151-167.

[4] Jacobsen, S. C., Wood, J. E., Knutti, D. F. and Biggers, K. B., 1986, "The Utah/MIT dextrous hand: work in progress", In D.T. Pham and W.B. Heginbotham edited *Robot Grippers*, pp. 341-389.

[5] Bekey, G. A., Tomovic, R. and Zeljkovic, I. 1990, "Control architecture for the Belgrade/UCS hand", In S.T. Venketaraman edited *Dextrous Robot Hands*.: Springer-Verlag New York pp. 136-149.

[6] Okada, T., 1986, "Computer control of multijointed finger system for precise object handling", In D.T. Pham and W.B. Heginbotham edited *Robot Grippers*, pp. 391-417.

[7] Ulrich, N., Paul, R. and Bajcsy R., 1988, "A medium-complexity compliant end effector" *Proc. IEEE Intl. Conf. on Robotics and Automation*, pp. 434-436.

[8] Doll, T. J. and Schneebeli, H. J. 1988, "The Karlsruhe hand" *Proc. on IFAC robot control, Karlsruhe*, pp. 383-388.

[9] Jongkind, W., 1993, "Dextrous gripping in a hazardous environment guidelines, fault tolerance and control" *Proc. IEEE Intl. Conf. on Systems Man and Cybernetics*, Vol. 1, pp. 509-514.

[10] Dubey, V. N. and Crowder, R. M., 2003 "Designing a dexterous reconfigurable packaging system for flexible automation" ASME Design Engineering Technical Conference, DETC2003/DAC-48812, Chicago, Illinois (USA).

[11] Caldwell, D. G., Medrano-Cerda, G. A. and Goodwin, M. 1995 "Control of pneumatic muscle actuators", *IEEE Control Systems Magazine*, Vol. 15, No. 1, pp. 40-48.

[12] Crowder, R. M., 1991, "An anthropomorphic robotic end effector" *Robotics and Autonomous Systems*, Vol. 7, pp. 253-268.

[13] Dubey, V. N. and Crowder, R. M., 2002 "A finger mechanism for adaptive end-effectors" ASME Design Engineering Technical Conference, DETC2002/MECH-34317, Montreal, Canada.

[14] Crowder, R. M., Dubey, V. N. and Chappell P. H., 1997 "A robotic end effector for unstructured environments"

American Nuclear Society, *7th Topical Meeting on Robotics and Remote Systems*, Augusta, Georgia (USA), pp. 452-459.

[15] Crowder, R. M., Dubey, V. N., Chappell, P. H. and Whatley, D. R., 1999, "A multi-fingered end effector for unstructured environments" *Proceedings of the IEEE Intl. Conf. on Robotics and Automation*, Detroit, Michigan, Vol. 4, pp. 3038-3043.

[16] Chappell, P. H., Fateh, M. M. and Crowder, R. M., 2001, "Kinematic control of a three-fingered and fully adaptive end-effector using a Jacobian matrix" *Mechatronics* Vol. 11, pp. 355-68.

[17] Dubey, V. N., 1997, "Sensing and control within a robotic end effector", *PhD Thesis*, University of Southampton, UK.

[18] Kumar, V. and Waldron, K. J., 1989 "Suboptimal algorithms for force distribution in multifingered grippers" *IEEE Transaction on Robotics and Automation*, Vol. 5, No. 4, pp. 491-498.

[19] Dubey, V.N., Crowder R.M. and Chappell P.H. 1999, "Optimal object grasp using tactile sensors and fuzzy logic" *Robotica*, Vol. 17, No. 6, November, pp. 685-693.

[20] Crowder, R. M., Dubey, V. N. and Chappell P. H. 2000, "Dynamic control of fingertip force using tactile sensors and fuzzy logic", *Sixth International Conference on Control, Automation, Robotics and Vision*, Singapore.