Design of a compact, dexterous robot hand with remotely located actuators and sensors

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***Abstract*—In this work, we report on our progress in the development of a new anthropomorphic robot hand at the University of Malta. Following a brief overview of the work carried out in our laboratory so far, we discuss in some detail and through a fresh perspective a number of important lessons that can be learned from the human hand, and that can be very useful in the development of an artificial hand that can ultimately match the human counterpart in the execution of many tasks. We present a new design for a robot hand with joint position and grasping force sensing, based on the specific approaches brought up in this discussion, and targeted to reproduce many of the capabilities of the human hand. In particular, all of the actuation and sensing devices of the hand are located remotely from the device, therefore facilitating the development of a compact and lightweight hand design. A prototype of the new hand has been constructed and is presented herein. Finally, we present the initial results of our analysis to demonstrate how the magnitude and location of grasping forces can be inferred from the sensor readings.**

Keywords—**teleoperation, robot hands, dexterity.**

I. Introduction

The design, development and analysis of dexterous robot hands remains an active research area worldwide, more than twenty years since the first models were announced in the early 1980s [1], [2]. Work in this area has followed two general paths. Along the first path, a number of research groups have worked to develop high performance robot hands, developing and using state-of-the-art technology through a high allocation of resources (e.g. [3], [4]). The results achieved by these research groups set the current overall boundaries of robot hand technology. Along the second path, other research groups have worked to develop robot hands that are intended to be used primarily as test beds, normally to test or to demonstrate one or a number of particular aspects that could potentially be applied to a truly dexterous robot hand (e.g. [5], [6]). These latter research groups have an important role to play, in that the relatively low financial investment normally allows them to easily implement major changes in their hand designs, in order to test new concepts and ideas in a relatively short time.

In the Industrial Automation Laboratory (IAL) of the Department of Manufacturing Engineering (DME) at the University of Malta (UOM) we have been working for a number of years to test and develop specific features that can be used in a dexterous robotic hand. In [7], a three-fingered, nine-joint gripper equipped with proximity and fingertip-force sensors was developed for use in automated assembly operations. A major focus of this work was the achievement of versatility in grasping through the use of a minimum number of actuators, and in fact only one actuator was required to operate the gripper. In [8], a five-degree-of-freedom hand and wrist system was developed, with major focus on taking a direction towards more anthropomorphism in the shape and function of the hand. Each of the three digits of the robot hand in [8] had two pitch joints to enable flexion and extension, and incorporated a passive switching mechanism that allowed a single actuator to drive the two joints successively. The anthropomorphic robot finger developed in [9] had three degrees-of-freedom (yaw motion and two pitch motions) actuated by miniature inbuilt DC motors fitted with encoders, and a mechanical coupling between the two outermost joints that mimicked the coupled motion of the equivalent human joints. In [10] a new sensor to sense incipient object slip during robotic grasping was developed and demonstrated.

In the present work, we have redesigned and rebuilt the hand presented in [8] to incorporate the following new features:

i. The addition of a third finger, so that the new hand now comprises three fingers and an opposable thumb;
ii. The addition of a new degree-of-freedom to each finger, so that each of the three fingers now has two independently driven flexion joints;
iii. An improved version of the mechanical joint coupling developed in [9], so that each finger now has a third (outermost) flexion joint that moves with the middle joint through a motion ratio that is similar to that of the human finger, and without the need for return springs;
iv. The incorporation of a mechanical joint coupling mechanism similar to that in (iii) above, between the inner and outer flexion joints of the thumb;
v. The addition of a rotational degree-of-freedom to the thumb;
vi. An improvement in the transmission system, so that the new hand now has eight remotely-located DC motors that actuate the eight degrees-of-freedom of the hand through lead screw and cable transmissions;
vii. The use of more accurate, remotely-located sensors for measurement of finger joint positions;
viii. The incorporation of a new grasping force sensing protocol based on measurement of the tensions in each of the actuating cables, using remotely-located sensors.

The major focus of the new robot hand is to move all of the actuation and sensing devices away from the main structure, in order to minimize the weight and complexity of the hand while retaining and even increasing the dexterity and anthropomorphism of the device.

II. Some Lessons from the Human hand

The development of artificial, anthropomorphic hands is generally greatly aided by the study of the anatomy of the human counterpart. Very often it has been found that the best approaches to the problems associated with the design of a robot hand are to adopt the solutions that have been obtained through natural evolution in the human hand.

The features that are demonstrated by the bone structure of the human hand (Fig. 1) already give clear indications of the degrees-of-freedom that are achievable by this organ. The palm, rather than consisting of one solid flat bone, is made up of a number of bony segments including the five metacarpals. This feature gives the palm the flexibility to cup sideways, and in particular the thumb metacarpal gives this digit the mobility to oppose the four fingers by a rotating movement that occurs within the palm. Each of the four fingers consists of three links, namely the proximal, middle (or intermediate) and distal phalanges, and three joints, namely the metacarpophalangeal (MCP) joint, the proximal interphalangeal (PIP) joint, and the distal interphalangeal (DIP) joint. Each of these twelve joints allows motion of the associated phalange principally in the pitch mode (flexion / extension), however the four finger MCP joints also allow limited motion in the yaw mode (abduction / adduction).

The second to fifth carpometacarpal (CMC) joints, at the base of each finger metacarpal bone, allow very limited motion, however the thumb CMC joint has a considerable degree of mobility. This mobility is due to the saddle-shaped articulation that is found between the base of the first metacarpal and the trapezium [11]. The thumb is able to carry out rotary and abduction/adduction motion at this joint, as two independent degrees-of-freedom. The MCP and DIP joints of the thumb allow motion in the flexion mode. The thumb has no PIP joint.

Although the human hand does accommodate a number of small muscles, the movement of the hand is mainly attributed to flexor and extensor muscles that are located in the forearm. Thus, the hand is able to achieve its dexterity while still maintaining a small size and compact shape through the use of *remotely located actuators*. The drive from these actuators (muscles) is transmitted to the hand through an intricate system of tendons, and enables flexion and extension of the fingers and thumb. The flexor tendons along the finger are held close to the skeleton by means of a tight fibrous sheath, in order to prevent bowstringing of the tendons as the fingers flex [11].

The human hand is broadly modeled to have 27 degrees-of-freedom: four for each of the four fingers, five for the thumb, and six for rotational and translational motion of the palm [12]. The six degrees-of-freedom pertaining to palm movement are ignored in detailed studies that focus specifically on hand operation, since they contribute only to gross movement of the hand. Essentially, these palm movements would be executed by the robot manipulator to which the hand is attached, and not by the hand itself. The number of degrees-of-freedom to be considered is therefore reduced to 21. Furthermore, it has been shown that a number of the degrees-of-freedom attributed to the fingers and thumb have limited or no practical range of motion, or only exhibit motion that is coupled to that of another joint [12], [13]. Of particular interest to this work are the following constraints found in the human hand [12]:

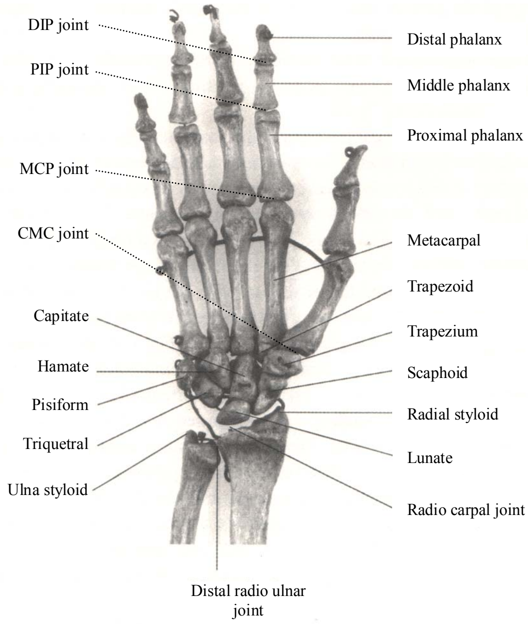


Figure 1. The bones of the human hand, and the locations of the finger and thumb joints (adapted by permission from [11]).

i. Flexion during normal motion is limited to $0^o - 90^o$ for the MCP and DIP joints and to $0^o - 110^o$ for the PIP joints.
ii. Normal motion of the DIP joint of each of the four fingers is coupled to that of the respective PIP joint, with a ratio of motions that is approximately given by

$$\theta_{DIP} = \tfrac{2}{3}\,\theta_{PIP} \quad (1)$$

iii. Abduction/adduction motion at the MCP joints is limited to a maximum of $\pm 15^o$, and is approximately zero for the middle finger and for the thumb.
iv. A significant number of joint movement combinations are not achievable by the human hand. For example, it is not possible to flex the little finger while keeping the ring finger fully extended.

Thus, the human hand achieves its dexterity without the need for largely unconstrained motion of all of its joints. Furthermore, it is generally accepted by the robotics community that the little finger may not give a significant contribution to manual dexterity, and indeed many robot hand models worldwide have omitted this fifth digit from their design. Preliminary studies on the contribution of the individual fingers to human manual dexterity were recently carried out in our laboratory, and have supported this perception [14].

The human hand has a number of sensing capabilities, with various degrees of accuracy and resolution. The tactile subsystem consists of various specialized cells within the skin that respond to stimuli such as light touch, low and high frequency vibration, deep pressure, stretch and temperature. It has been found that the hand can detect forces as low as 0.0037 N, and discriminate between points of application of forces that are about 1 mm apart at the fingertips (see [15] and references therein). Pain receptors take the form of free nerve endings in the skin. Muscle spindles located within the small muscles of the hand provide information on muscle length and therefore on the joint position [11]. Other specialized receptors located in the tendons provide information pertaining to muscle tension, and therefore, indirectly, pertaining to forces applied by the hand.

In spite of the presence of the various sensory capabilities described above, the hand relies to a large extent on vision feedback in the execution of most tasks. In practice, for example, the feedback available from the eyes may provide more accurate information than that available from the muscle spindles in the hand, in the determination of the finger joint positions.

Some important lessons that can be learned from the human hand, and that can be applied to the design of a dexterous robot hand, can therefore be summarized as follows:

i. In order to achieve dexterity of the robot hand while at the same time retaining small size and compactness of the device, it may be necessary to use remotely located actuators;
ii. The limitation or even elimination of certain degrees of freedom of the robot hand, in comparison to and/or in imitation of the human hand, may not result in significant or even perceptible penalties in dexterity;
iii. Useful information about grasping forces may be obtained through the use of tension sensors in the actuation / transmission system of the robot hand. Such sensors can be mounted *away from the hand*, i.e. close to the remotely located actuators. This contributes to a simpler and lighter hand structure;
iv. In order to make a fair comparison between a human and a robot hand, it is important to note that a human hand is normally used in conjunction with very high quality visual feedback (from the human eye) and with a sophisticated knowledge base (the human brain). In such a situation, and particularly in the application to standard everyday tasks, some of the sensory capabilities of the human hand may be redundant, and may be downgraded or omitted from the robot hand without much degradation in performance. This is particularly true when the robot hand is to be used in teleoperated mode.

In the following sections, we present a design for a new robot hand, based in large part on the particular lessons, learned from the human hand, that have been outlined above.

III. Design of the Robot Hand

A. *Conceptual Considerations*

Based on the discussion given in the previous sections, it was decided to design a new anthropomorphic robot hand that incorporated three fingers and an opposable thumb. Each of the fingers in the new design has three joints allowing flexion motion, equivalent to the MCP, PIP and DIP joints of the human finger, and hereinafter referred to as finger joints 1, 2, and 3 respectively. Each finger has two independent degrees-of-freedom, with joint 3 motion coupled to joint 2 motion to match the ratio given by equation (1). Joints 1 of the fingers do not allow abduction / adduction motion. The thumb has three joints equivalent to the human CMC, MCP and DIP joints, and hereinafter referred to as thumb joints 1, 2, and 3 respectively. In the present model, for the thumb, it was decided to omit independent motion of joint 3, and also to omit abduction / adduction motion at joint 1. The thumb therefore has two independent degrees-of-freedom, with joints 2 and 3 executing coupled flexion motion in a manner similar to that of the fingers (but with a ratio of 1:1), and with joint 1 executing rotary motion to enable the thumb to oppose the three fingers.

All actuators and sensors are located remotely from the hand, to minimize weight and structural complexity, and in order not to incur unnecessary limitations on size and compactness of the design. Drive transmission for the eight primary joints of the hand is achieved through the use of flexible sheathed cables. Cable movement (position) is sensed at the remote end of the cables, close to the actuators, and provides information on the finger and thumb joint positions. Although the remote location of these position sensors may contribute to less effective position control of the finger joints if there is no other sensory feedback, it is in line with an overriding philosophy of this design that the hand will be used primarily in conjunction with other sensing capabilities such as vision, as is the human hand, and therefore that optimal position feedback for control purposes is not mandatory. The new robot hand is also equipped with cable tension sensors, located at the remote end of the cables beside the position sensors.

B. *Solution Sythesis*

Several options for finger structure have already been implemented in other robotic hand research projects described in the literature, and all have their respective advantages and disadvantages. One of the first issues that must be considered in a new project is whether to employ an endoskeletal or an exoskeletal approach to the design. Most of the robot hands built to date have relied on an exoskeletal structure, where the fingers and palm are built in the form of an outer shell that protects and supports the actuators, transmission systems, joints, sensors, etc. More recent literature has advocated the development of an endoskeletal structure, with an internal skeleton on which all of the other hand components are built and mounted

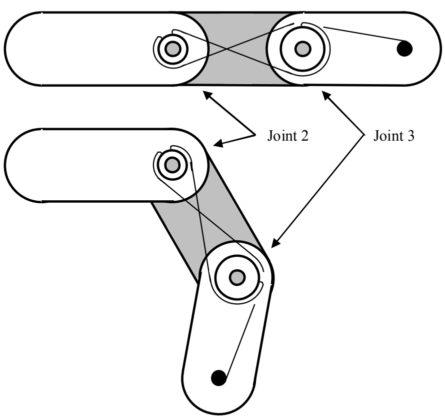


Figure 2. The cable and pulley coupling mechanism between joints 2 and 3 of the robot finger, shown in extended and partly flexed configurations.

[16]. The human hand is based on an endoskeletal design, and indeed this can be considered to be another lesson that can be learned from the biological model. Essentially, an exoskeletal design offers advantages in mechanical simplicity, while an endoskeletal design enhances the potential dexterity of the robot hand through facilitation of the incorporation of integrated sensors and through increased manipulation capability due to compliant contacts. While there can be no doubt that the future of dexterous robot hands will rely heavily on endoskeletal designs, it was decided to pursue a more traditional exoskeletal approach in this work, and to focus more on the features detailed in section *III A* above.

After considering several alternatives, it was decided to employ a parallel plate design for the main structure of the palm and digits, and to use shaft and pulley systems at the joints. An innovative addition to our design was the use of a new coupling mechanism between joints 2 and 3 of the fingers, by which the required coupling ratio could be obtained for both the flexion and extension motions using cables without the need for a return spring. This mechanism is illustrated in Fig. 2. When the intermediate link is driven through an angle θ (by means of a separate driver pulley that is not shown in Fig. 2) the cables shown in the figure cause the distal link to rotate by an angle ⅔θ relative to the intermediate link. This ratio is obtained by selecting appropriately sized pulleys for the mechanism.

The abduction angle of the thumb was set at 70°, i.e. approximately equal to the maximum abduction achievable by a human thumb. Through inspection of the human hand it was noted that when the human palm is placed on a flat surface, the thumb has a natural angle of twist of about 20° to this surface, as illustrated in Fig. 3. It was decided to incorporate this feature in our robot hand. The method of attachment of the thumb to the palm is illustrated and described in Fig. 4. Rotation of the thumb was achieved using a cable and pulley transmission as shown in Fig. 4*(a)*.

Actuation was achieved by rotary DC motors and lead

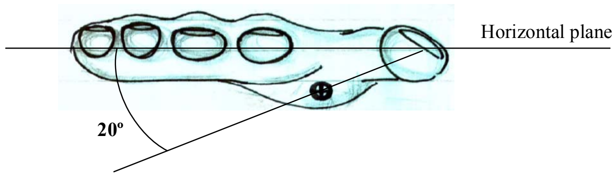


Figure 3. Natural twist angle of the human thumb (approximate).

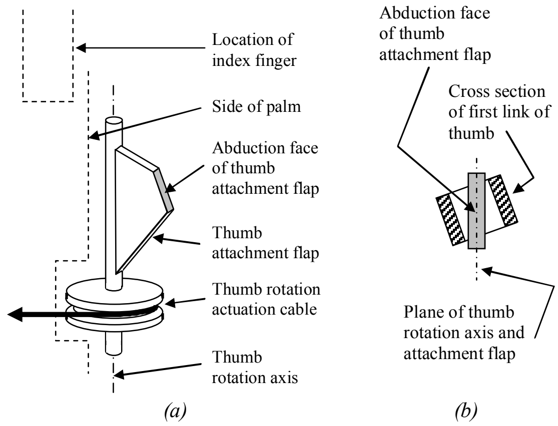


Figure 4. *(a)* Thumb attachment flap and rotation mechanism in the robot hand. The normal to the grey-shaded face of the flap is inclined at 70° to the side of the palm and determines the fixed abduction angle of the thumb. *(b)* Attachment of the thumb to the flap, showing the 20° twist of the thumb with respect to the thumb rotation axis.

screw mechanisms, via flexible sheathed cable transmissions to pulleys at the individual joints of the hand. Cable tension was measured using a concept based on Hooke's law, whereby the extension of springs placed in series with the cables was measured using linear potentiometers. The position of the cable, for each joint, was measured using a separate potentiometer. The final conceptual designs for the actuation and sensing systems of the robot hand are shown schematically in Fig. 5.

C. Solution Analysis and Detailed Design

The dimensions of the palm and fingers are based on typical values for the human hand, with some provisions for ease of manufacture. The three fingers were designed to have equal dimensions, however the palm was designed such that the first joint of the middle finger is located 4 mm distal of the other two finger first joints. Thus when the fingers are fully extended, the middle finger extends further outwards as in the human hand. The lengths of the links of the fingers and thumb of the robot hand are summarized in Table I. Each of the digits is 24 mm wide and 22 mm high. The palm has dimensions 105 X 80 X 26 mm.

TABLE I
LINK LENGTHS

	Links			
	Metacarpal link	**Proximal**	**Intermediate**	**Distal**
Finger	–	50 mm	27 mm	28 mm
Thumb		40 mm	–	29 mm

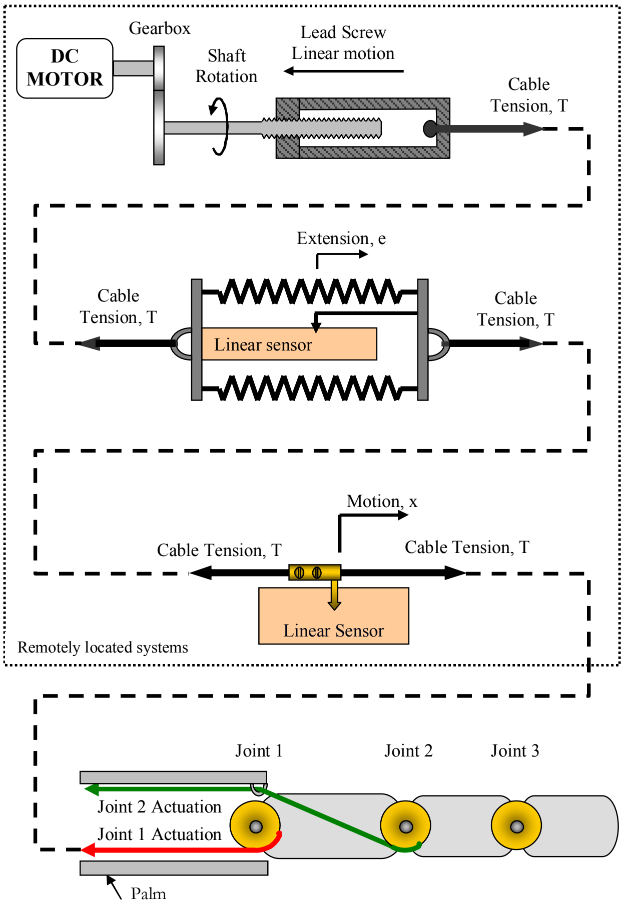


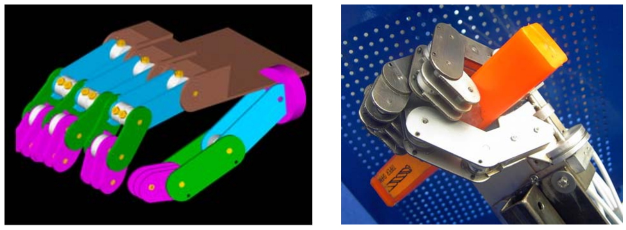
Figure 5. Conceptual layout of the actuation and sensing systems for one of the joints of the robot hand, showing, from top to bottom: motor and lead screw; cable force sensor; cable position sensor; and cable attachment to the joint 1 pulley.

In order to emulate the force capability of the human hand, each digit of the robot hand is able to exert a maximum force of approximately 15 N at the fingertip. Based on the use of pulleys that fit completely within the structure of the fingers, this translates to a maximum cable force requirement of about 260 N.

Each independent joint of the robot hand is driven by a 7.2 V permanent magnet DC motor with a maximum speed of 19,000 RPM and maximum output torque of 3.75 Ncm. The drive is routed through a 50:1 reduction gearbox. The lead screw was selected such that the required cable tension could be achieved, while giving a maximum cable speed of about 10 mm/s, equivalent to about 90^o finger joint rotation per second. In the current model, the drives are single-acting, with remotely-located spring return mechanisms to extend the finger and thumb joints. The design allows for easy conversion to a double-acting drive system.

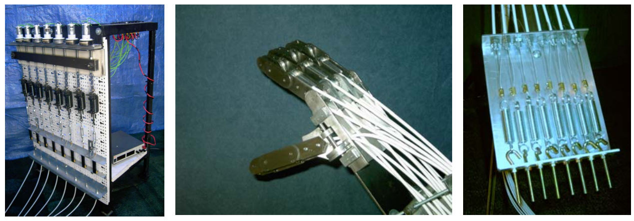
Each of the cable force sensing devices consists of a linear potentiometer of range 30 mm, and two helical springs, each of stiffness 6 kN/m, connected in parallel as indicated in Fig. 5. The linear potentiometer used for position sensing is identical to that used for force sensing.

A CAD drawing of the robot hand is given in Fig. 6*(a)*, and the mechanical structure of the constructed hand is shown in Fig. 6*(b)*. Fig. 7 gives a dorsal view of the hand, and shows the installation of the remotely located actuators, sensors and return springs.



(a) *(b)*

Figure 6. *(a)* AutoCAD® drawing of the robot hand; *(b)* the constructed robot hand.



(a) *(b)* *(c)*

Figure 7. *(a)* Actuator and sensor remote installation; *(b)* attachment of cables to the robot hand; (c) remote installation of return springs.

The robot hand will be controlled by a PC, through a data acquisition card having analogue and digital inputs and outputs. A block diagram of the control structure is given in Fig. 8.

IV. Interpretation of the Force Sensor Readings

For each finger of the robot hand, the tension T_1 that is required in the actuating cable at joint 1, to counteract a force F acting normally on the distal phalange at a distance d_3 from joint 3, as shown in Fig. 9, is given by

$$T_1 r_1 = F[\ell_1 \cos(\theta_2 + \theta_3) + \ell_2 \cos\theta_3 + d_3] \qquad (2)$$

with frictional effects neglected and where r_1 is the radius of the proximal phalange drive pulley at joint 1. Under these conditions the tension T_2 that is required in the actuating cable at joint 2 is given by

$$T_2 r_2 = F[\ell_2 \cos\theta_3 + d_3(1 + {}^{r_{c1}}\!/\!_{r_{c3}})] \qquad (3)$$

where r_2 is the radius of the intermediate phalange drive pulley at joint 2, and where r_{c1} and r_{c3} are the radii of the coupling mechanism pulleys at joints 2 and 3 respectively. The angular position of joint 3 is given by

$$\theta_3 = {}^{r_{c1}}\!/\!_{r_{c3}}\, \theta_2 \qquad (4)$$

In our design ${}^{r_{c1}}\!/\!_{r_{c3}} = {}^2\!/\!_3$.

The magnitude of the grasping force F can therefore be estimated from equations (2) and (4), using the sensor readings of cable force T_1 and joint position θ_2. If the distance d_3 is not known, then F and d_3 can be estimated from equations (2), (3), and (4). Similar information can be obtained for the thumb.

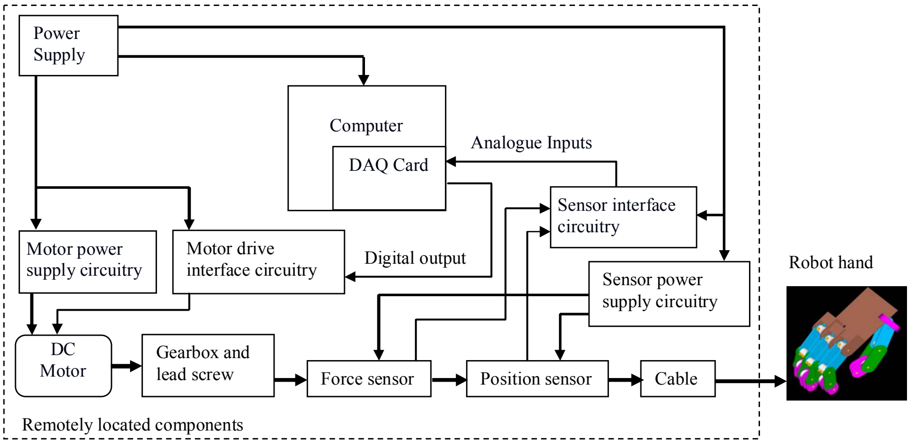


Figure 8. Block diagram for the control of one of the joints of the robot hand.

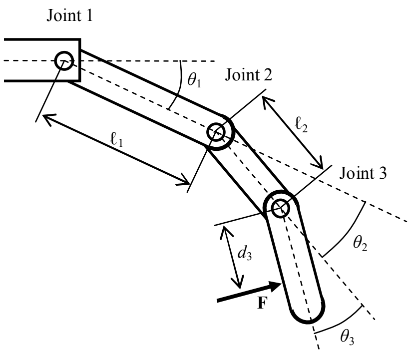


Figure 9. Kinematic model of the robot finger.

V. Conclusion

A new eight-degree-of-freedom robot hand has been designed, based on key insights that can be obtained from the human hand. In particular, all actuators and sensors are located remotely from the hand, therefore allowing the design of the hand structure to focus more on issues pertaining to the optimization of weight, size and shape to maximize dexterity. A prototype of the robot hand has been built, and is currently undergoing preliminary testing in our laboratory. Current work also involves the further development and integration of the control system of the hand, and the incorporation of double-acting actuation in the joints to eliminate the return springs. Future work will focus on the use of the hand to investigate specific issues related to grasping, manipulation and dexterity, and further upgrading of the hand to incorporate more sensing capabilities and more degrees-of-freedom.

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