Undergraduate mechatronics research case study:

Contributing towards a dexterous robot hand

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Abstract

The importance of implementing a strong project-based approach to undergraduate mechatronics education, and the further enhancement obtained through the introduction of a research aspect to these projects, have been emphasized in the literature. In this work we document our experience in the immersion of final year undergraduate mechanical engineering students into the research programme of the Department of Industrial and Manufacturing Engineering of the University of Malta, through supervised undergraduate projects that build upon each other from year to year, eventually leading to valid research publications at an international level. We focus on the specific area of robot hands, and later on one specific extended project as a case study. We first describe briefly a selection of research oriented undergraduate projects in this area carried out during the last twelve years. The paper then focuses on one particular project among those described, involving the development of an eight-degree-of-freedom anthropomorphic robot hand that is based on observations of both the attributes and the limitations of the human hand. The robot hand is intended to be used as a teleoperated slave device, and a particular objective is to reduce size and weight through the remote location of all of the actuators and sensors. The paper gives a detailed rationale for the hand design, followed by descriptions of the kinematic, mechanical, actuation, sensing, and control systems of the constructed prototype. This is followed by a description of sensor calibration procedures and results. The paper concludes with a brief discussion of the significance of this work, addressing both the educational and research aspects, and of future directions to be taken.

Keywords: mechatronics education, robot hands, teleoperation

Introduction

The importance of implementing a strong *project-based learning* aspect to undergraduate mechatronics education has been highlighted by several authors (e.g. [1, 2, 3, 4, 5]). Typically, the project portion of a Mechatronics degree programme, or of a Mechatronics study unit, involves the design and manufacture of a system that incorporates mechanical moving parts controlled through electronic circuitry, and normally involving sensory feedback and/or interfacing to a computer-based controller (i.e. a mechatronic system). Some educational institutions have taken the challenge a step further, and have incorporated a substantial research element into the undergraduate student projects, either in a laboratory setting (e.g. [6]), or in an industrial setting (e.g. [7]). Indeed, the trend to expose undergraduates to a research environment has been emphasized also in other areas of mechanical engineering (e.g. [8, 9]), and is known to greatly enhance the learning process.

The undergraduate Engineering degree programme at the University of Malta, while undergoing many changes over the years, has always incorporated a substantial project that is carried out by the student during the final year of studies. Each project is unique, and the various subject areas covered and project titles have depended on student interests, academic staff expertise, and available resources. Over the last fifteen years, a substantial percentage of final (fourth) year projects have involved a strong research element, often leading directly to research publications at an international level. In this work we document some of the results achieved using this approach in the Robotics and Industrial Automation Laboratory (RIAL, formerly the Industrial Automation Laboratory, IAL) of the Department of Industrial and Manufacturing Engineering (DIME) of the University of Malta (UM). We focus on one specific research area within the field of Mechatronics, and later focus further on one extended project as a specific case study. Our results show that this approach serves not only to enhance the educational experience of the students, but also to give them a head start in making valid research contributions in their freshly chosen field of interest.

Over the last twelve years, one of the major ongoing research activities within the RIAL has involved studies related to robot hands. The research has involved mainly the identification and investigation of novel concepts that can be applied to this class of devices. At the same time a number of hand prototypes have been developed in the laboratory, mainly to test these concepts. These research projects have involved the input from academic staff members, dedicated researchers, postgraduate students, and often also final year undergraduate engineering students. The involvement of undergraduate students has meant that this work, while providing valid research results in its own right, has also been a cornerstone of undergraduate mechatronics education within the department. We have selected a small number of projects in this area to which senior undergraduate students gave the major contribution, and we first describe these projects briefly and showcase the results obtained. The paper then focuses in more detail on one of these projects, involving the development of a dexterous robot hand with remotely located actuators and sensors.

This paper has dual objectives: to present the results of the work done to develop the robot hand; and to highlight the contribution of this research activity and of other similar projects to mechatronics education within DIME.

A brief introduction to dexterous robot hands

Globally, research work aimed towards the development of a truly dexterous robot hand, and in particular the emulation of the human hand, has been ongoing for more than a quarter of a century. The seminal works in this regard are widely considered to have been those carried out at Stanford University (the “Stanford/JPL hand” [10]), and at the University of Utah culminating in the development of the “Utah/MIT dextrous hand”

(UMDH) [11], in the early to mid 1980s. Even in the early design version reported in [11], the UMDH already had a relatively high degree of geometric and functional similarity to the human hand (i.e. anthropomorphism), and included three fingers and an opposed thumb with 16 joints in total, as well as touch, force, and joint position sensors. In particular, the UMDH actuators were located remotely, to reduce weight and to free up space in the hand itself.

Over the ensuing years, research in the development of dexterous robot hands has been prolific, and a large number of models, with different features and properties, and utilizing various different technologies, have been developed in numerous institutions worldwide (e.g. [12, 13, 14]). The overriding aim in most of these cases has remained the reproduction of the features and functions of the human hand, the main reason for this being the potential for better compatibility with the multitude of objects that would originally have been designed for human manipulation, and with the multitude of tasks that would originally have been intended for human implementation.

Undergraduate research project showcase: Towards a dexterous robot hand

In the RIAL, research work in this field has been ongoing for over a decade, often involving, to varying extents, senior undergraduate engineering students. In many cases, specific projects assigned to undergraduate students build upon the results of earlier projects, and in this way the students have a clear sense of contribution to a growing R&D programme within the laboratory. Whenever there are results that reach an adequate standard, the students are encouraged to either lead, or to contribute actively to, a research publication based on the project. These projects therefore combine an important part of undergraduate mechatronics education within the department, at both the theoretical and practical levels, with a valid contribution to productive research activity. In this section we review some of the achievements realized under this programme.

In 2000, a three-finger, nine-joint gripper, equipped with force-sensitive resistor (FSR) fingertip force sensors, and incorporating a diffuse photoelectric palm proximity sensor, was developed for use in automated assembly operations [15]. An important objective of this work was to demonstrate that a considerable degree of versatility could be achieved even using a single actuator for the whole hand, through the use of cleverly designed mechanical, transmission, and sensory systems. Between 2001 and 2005, this gripper was integrated into a flexible, vision and robot based, material transfer system that could recognize, locate and pick up different items placed randomly on a moving flat-belt conveyor [16]. Figure 1 shows the versatile gripper and its application to the flexible automation system.

[Take in Figure 1]

In 2001, a new, more anthropomorphic, robot hand and wrist system was designed and built. The hand had two fingers and an opposed thumb, with each digit consisting of two passively coupled joints and driven by a separate motor. The wrist consisted of separately actuated pitch and roll joints, so that in total the system had five degrees of freedom. The work focused on replicating as closely as possible the shape, size, natural motions and applied forces of the human hand, while keeping the complexity of the robot hand and wrist to a minimum. Design force requirements were obtained through an extensive series of experiments to measure human grasping forces, and the joints in each robot digit were coupled to move in succession using a novel passive switching mechanism. The original model was driven by five remotely located stepper motors and was teleoperated in open loop mode through a knob based input console, and using the analogue inputs and digital outputs of a data acquisition card mounted on a PC. During 2002 and 2003 a whole hand position input device (glove) [17] was developed to teleoperate the robot hand. The glove incorporated a number of new features not previously found in the literature, including measurement of the roll position of the human forearm, and a novel adjustment capability to fit a wide range of human hand sizes. In 2005 hand actuation was converted to servo control, and the results of this complete hand project were published in [18]. The robot hand and the glove input device are shown in Figure 2.

[Take in Figure 2]

During 2004 and 2005 a new anthropomorphic robot finger, actuated using inbuilt miniature DC motors, was developed [19]. This finger was based closely on the human counterpart, and incorporated an abduction / adduction (yaw) joint and three flexion / extension (pitch) joints. The yaw joint and the first two pitch joints were actuated using independent motors, while the outermost pitch joint was mechanically coupled to the middle joint in a way that reproduced the movement ratio of the human equivalent. The robot finger is shown in Figure 3. This project included also a full kinematic analysis (including position, velocity and force analyses and motion path planning) and simulation of the new robot finger. The paper also proposed an ideal phalange (link) length ratio to maximize workspace volume for an anthropomorphic finger with this joint structure.

[Take in Figure 3]

In 2006, a series of experiments to measure human manual dexterity while selectively constraining certain features of the hand was carried out, in order to deduce the contribution of the selected features to overall manual dexterity [20]. Further experiments were carried out in 2008 [21]. These experiments were meant to provide guidelines on feature prioritization and selection when designing anthropomorphic robot hands.

The latest RIAL anthropomorphic robot hand, which is the main subject of this paper, was developed between 2006 and 2009. The main focus in this model was to move all of the actuators and sensors away from the main device, in order to eventually minimize the weight of the hand and to maximize space-related performance and dexterity features. The preliminary design and the first version of the prototype have been presented in [22]. In the remainder of this work the detailed philosophy behind the hand design, and the details of the latest design version and prototype, are given, together with a report on the calibration of the position and force sensors and the control approach to be used for the hand.

Rationale for the hand design

A main objective in the design of this RIAL hand was to maximize the resemblance to features of the human hand while minimizing complexity and cost of the device. This goal was approached by carrying out an objective review of the human hand, to understand not only the attributes of this natural organ, but also the often neglected constraints and limitations in its structure and operation. These limitations clearly have little detrimental effect on the dexterity of the human hand, but they may have profound implications for design simplification in a robot hand.

One of the first points to note is that most of the muscles that effect human finger movement are in fact located in the forearm and not in the hand itself. The human hand therefore mainly uses remotely located actuators. Thus, wherever a robot hand has been constructed using inbuilt actuators, its creators have in fact tried to achieve something that not even the natural hand has succeeded, or chosen, to do. Essentially, by allowing the concession to locate the strong (and large) actuators (muscles) in the forearm, the human has managed to evolve a small and nimble, yet strong, hand.

A second note is that although the human hand can be broadly modeled to have 21 intrinsic degrees of freedom (e.g. [23]), these motions are in fact subject to a considerable number of constraints. Of particular interest are the finger joint position limitations in flexion and in sideways motion (abduction/adduction), and the coupled motion of the two outermost joints on each finger [24]. By taking cognizance of some of these motion constraints and translating them into design relaxations, it is noted that the dexterity of a robot hand may not be reduced significantly if (i) finger joints are allowed only limited motion as in the human hand; (ii) the outermost joints are not designed to move independently and (iii) sideways motion of the fingers is limited. Furthermore, it may be possible to omit the little finger altogether with little penalty in dexterity, as indicated in [20].

A third point to be made is that significant force sensing in the human body is provided by specialized sensors (Golgi tendon organs) that are located at the interface between the muscles and the tendons [25]. Thus, when a human is grasping an object with his hand, part of the sensation and evaluation of the applied force is coming from a sensing of tendon tension in the forearm. The human hand is therefore equipped with remotely located tension-based force sensors, and this concept can be applied also in an artificial hand, thus contributing to a lighter and simpler hand structure. Furthermore, the Just-Noticeable-Difference (JND) of grasp force sensing by the human hand is of about 7% [26], i.e. the grasp force resolution is considerably low.

A fourth point is related to joint position sensing in the human hand, in the absence of visual feedback. The authors observe that with eyes closed it is difficult to move the finger joints in small angular increments or to return accurately to previously set positions. Moreover, after a few seconds without movement the sensation of finger position is lost and it may become difficult even to determine whether the finger is flexed or not. The inaccuracies in finger position sensing in the absence of vision have been well documented in the literature (e.g. [27, 28]). Thus the human hand appears to rely very heavily on visual sensing for joint position feedback. The JND for the positions of the two innermost joints of the human finger has been found to be about 2.5° [26].

Apart from its reliance on the human eyes for visual feedback, the human hand relies almost exclusively on the human brain for control. In the context of these two major dependences, the human hand can therefore be considered to function very much as a teleoperated, rather than an autonomous, device! Thus, robot hands in the literature that focus on autonomous control through the installation of high resolution sensors and advanced controllers mounted on the hand itself, may in fact be setting goals that exceed the design specifications set by the anatomical human hand.

The above facts have been used as the guiding principles in the design of the RIAL dexterous hand. The hand is intended to be used solely as a teleoperated slave device, guided by a human who would wear a master glove input/output device, and who would act as the controller with the aid of vision and force feedback. Position sensors on the glove device will provide the reference signals for gross position control of the robot hand, with the fine position control being obtained through the visual feedback. This strategy reduces greatly the demands on the inherent position sensing system of the robot hand. The force feedback on the glove device is envisaged to be effected through an actuator and cable system which provides resistance to the human finger movement through the application of an appropriate cable tension, as described in [29] and [30], and as is also commonly the case in other haptic gloves (e.g. [31, 32]). Thus, in the RIAL robot hand, it is sufficient to sense only cable tensions for force feedback during grasping, with the aim of using these readings to control the analogous cable tensions in the feedback actuation system of the master glove. It is envisaged that while wearing the haptic glove, the human controller will quickly learn to interpret the resistance to finger movement as a grasping force.

Kinematic and mechanical structure of the hand

The RIAL Robot Hand is based on an exo-skeletal design with internal cable and pulley systems, and has three fingers and an opposable thumb. The joints are located at positions similar to the ones found in the human hand. Each of the fingers has three flexion joints, with the inner two actuated independently, and with the outer joint passively coupled to the middle joint using an improved version of the coupling introduced in [19] with a coupling ratio of 1:⅔ (see figure 4). The thumb has two flexion joints coupled in the same manner as above and driven by one actuator, as well as a rotary joint to bring it towards and to opposition to the fingers, driven by a separate actuator (figure 5).

[Take in Figure 4]

[Take in Figure 5]

The present prototype of the robot hand, intended for preliminary experimentation and concept testing, employs a stainless steel structure, and weighs 1.48 kg. It is designed for joint speeds of about 90°/s and fingertip grasping forces of 15 N. It is slightly larger than the average size of the hand of a human male, with a total length (palm plus middle finger) of 210 mm. A CAD drawing and photograph of the hand are shown in figure 6.

[Take in Figure 6]

A remote and integrated actuation and sensing system

The actuation system of the hand is made up of eight remotely located DC motors, one for every DOF. Each motor is linked to a reduction gearbox and a leadscrew, and is connected to one finger joint through a double acting sheathed cable transmission system. This cable transmission system is analogous to the tendon system found in the human hand.

The hand is further equipped with position and force sensors that are also remotely located and that are integrated with the cable transmission system. There is one position and one force sensor for each of the eight DOFs. Both types of sensor are based on linear potentiometers, as illustrated in figure 7. A schematic of the integrated actuation and sensing system is included in the figure. Joint movement is achieved through position control of the DC motors.

[Take in Figure 7]

Computer interfacing

The system uses two NI USB-6009 DAQs with eight analogue input channels each, and the required software and graphical interface were designed using LabVIEW Ver. 7.1 [33]. Figure 8 shows the front panel of the position sensing software. The angular positions of the joints are calculated from the input voltages using different equations that were obtained through the individual and separate calibration of each position sensor. The calculated results are outputted on counters, and these values represent the estimated angular position of each joint. The force sensing system uses similar software design, where the cable tension is calculated from the output voltage of the force sensor circuitry.

[Take in Figure 8]

The demonstration program also allows the user to move all of the finger joints to specified positions as required. The user enters the desired joint positions, and three LEDs for each joint on the front panel tell the user whether the joints are closing or opening, or that the joints are within two degrees of the desired position.

Calibration of the position and force sensors

To transform the voltage readings from the position sensor circuitry into the respective angles, it was essential to find a relationship for each joint between the voltage reading and the actual angular position of the joint. These relationships were obtained by curve fitting to extensive experimental calibration data, obtained using custom built joint angle measurement devices (see figure 9). The equations for all joints were then used in the development of the computer-based position measurement system described in the previous section.

[Take in Figure 9]

A typical joint position calibration plot, based on three sets of readings of fifteen values each, is shown in figure 10. In the next stage an accuracy measurement for each joint was performed. Here, fifteen readings of random positions were taken for each joint, and the true (physically measured) angle was compared to the one displayed by the software, as calculated through the equations obtained by calibration. A summary of the results of these experiments can be seen in table 1.

[Take in Figure 10]

[Take in Table 1]

As can be seen, the results achieved are quite satisfactory. A global average error of only 1.85° and an average maximum error of 3.9° were obtained. One can also see that the thumb flexion joint has an average error of just 0.6° and a maximum error of 2°. These errors can be improved using higher quality linear position sensing devices. In the context of the rationale for the hand design described above, these results indicate that remote position sensing can be, in fact, performed with the method used.

The force sensing, or cable tension measurement, system was calibrated for each of the eight degrees of freedom of the robot hand. This was done by loading every sensor in increments of 0.91 kg on a calibration rig, up to a maximum mass of about 20kg. Five such cycles for each sensor were performed, some of which involved the unloading of weights rather than the loading so as to check for hysteresis. The positive outcome of this stage can be seen in figure 11, where all the points on the graph lie in good proximity to the curve of best fit. The outputs of the force sensor potentiometer circuits are converted to force readings using LabVIEW, in a manner similar to that used in the position sensing system.

[Take in Figure 11]

Integrative education aspect of this project

The approach taken in this project has been to engage successively two undergraduate final year students. The first student (MA) worked on the development of the basic mechatronic system and on the first prototype. Subsequently, the second student (DJC) worked on the system upgrade and refinement, as well as on the acquisition, interpretation and implementation of the calibration results. Both students worked under the close and detailed guidance of their supervisor (MAS) as an advisor and for the detailed formulation of the rationale and objectives. A device as complex as an anthropomorphic robot hand would present a major challenge to any researcher, but more so, when undergraduate students are involved, we have found that such a challenge provides a unique opportunity for these students to apply their various pedagogically acquired skills in an integrated manner, while at the same time placing considerable demands on their creativity and resourcefulness. Indeed, the summary report presented herein hardly does justice to the effort expended by these students to the extensive brainstorming; literature review; research discussion; design concept generation, evaluation and selection; embodiment and detailed design development of the integrated mechatronic system; and the construction, testing, evaluation and calibration of the final system. These challenges constitute an excellent preparation for the students, whether for an industrial or for an academic career, particularly where the focus is to be on research and development.

Conclusion

As discussed above in the section dealing with the hand design rationale, the main thrust of this work has been to demonstrate that by focussing as much on the limitations as on the attributes of the human hand, an artificial hand can be developed that would potentially be able to match the performance of the natural organ to a significant extent, as long as the artificial and natural hands were applied in similar ways and compared on a level playing field. In this work it has been argued that the human hand, as viewed distal to the wrist, has the characteristics of a teleoperated device, in that it relies very heavily on the human brain and on visual feedback for control. This and other observations made in the rationale section of this paper mitigate towards less stringent requirements for the position and force sensing systems of a robot hand, as long as this is intended to be used only in a teleoperated mode, and more so if the master device is to be of the whole hand input/output type.

A necessary requirement for the design of an artificial hand to be used under these conditions, remains the replication of the mechanical structure and kinematics of the human hand to the highest extent possible, in order to better enable the execution of the many complex tasks that can be carried out manually by humans. In this there can be no short cut. However, in replicating the mechanics of the human hand, the physical limitations of the natural organ should be borne in mind and replicated also, with the aim of avoiding the over design of the robot hand.

The current model of the RIAL hand still lacks a number of key elements, related to its potential to replicate human performance in a remote environment through teleoperation. One of these is touch feedback, a sensory element that is crucial for successful performance by teleoperated hands. A second missing element is the abduction/adduction function, which in spite of the observation made in the rationale section above may still be critical for certain tasks. Thirdly, the number of independent degrees of freedom of the thumb of the robot hand is less than that on the human counterpart. A fourth missing element is the soft and stretchable exterior of the fingertips, which in the human hand may give a huge contribution to the general compliance, conformity, and manipulation capability of the organ. Furthermore, the use of more advanced materials can serve to reduce significantly further the overall weight of the hand, while improvement of the sheathed cable transmission system can target the reduction of frictional resistance in the actuation system.

Many of these specific issues pertaining to the RIAL hand will need to be addressed mainly by postgraduate / post-doctoral researchers in the laboratory. However, at the same time this line of research will continue to offer many opportunities for undergraduate students to participate in exciting, challenging, and highly educational niche projects, enriching the learning experience while continuing to provide a valid contribution to the R&D activity of the department.

Acknowledgement

This work has been partly funded by the University of Malta under research grant numbers 73-528 and 31-353.

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Table 1. Summary of joint position accuracy measurement results

Joint	**Average error**	**Maximum error**
Thumb rotation	0.9^{o}	2^{o}
Thumb flexion	0.6^{o}	2^{o}
Index finger Joint 1 (“MCP”)	3.1^{o}	6^{o}
Index finger Joint 2 (“PIP”)	1.4^{o}	3^{o}
Middle finger Joint 1 (“MCP”)	2.4^{o}	4^{o}
Middle finger Joint 2 (“PIP”)	3.0^{o}	5^{o}
Ring finger Joint 1 (“MCP”)	1.7^{o}	4^{o}
Ring finger Joint 2 (“PIP”)	1.6^{o}	5^{o}

Figure captions

Figure 1. The flexible automation system; Inset: the versatile gripper.

Figure 2. The teleoperated hand and the glove input device; Inset: measurement of human grasping forces.

Figure 3. The anthropomorphic robot finger. Left: extended, with yaw movement; Right: fully flexed.

Figure 4. The cable and pulley coupling mechanism between Joint 2 and Joint 3 of the robot finger, shown in extended and in partly flexed configurations.

Figure 5. Top: natural twist angle of the human thumb (approximate); Bottom left: thumb attachment flap and rotation mechanism in the robot hand; Bottom right: attachment of the thumb to the flap, showing the 20^o twist of the thumb with respect to the thumb rotation axis.

Figure 6. The new RIAL anthropomorphic hand. Left: CAD drawing; Right: hand prototype.

Figure 7. Schematics of the actuation and sensing systems for one finger of the hand. Top left: cable position sensor; Top right: cable force sensor; Bottom: dual double acting actuation system, showing locations of the position and force sensors. The actuation / sensing system is located remotely from the hand, and transmission occurs through flexible sheathed cables.

Figure 8. LabVIEW position sensing program – front panel display.

Figure 9. Joint position measurement devices for calibration. Left: innermost and middle flexion joints of the finger; Right: thumb rotation joint.

Figure 10. Position calibration curve for the middle flexion joint of the middle finger.

Figure 11. Calibration curve for the force sensor of the middle flexion joint of the middle finger.

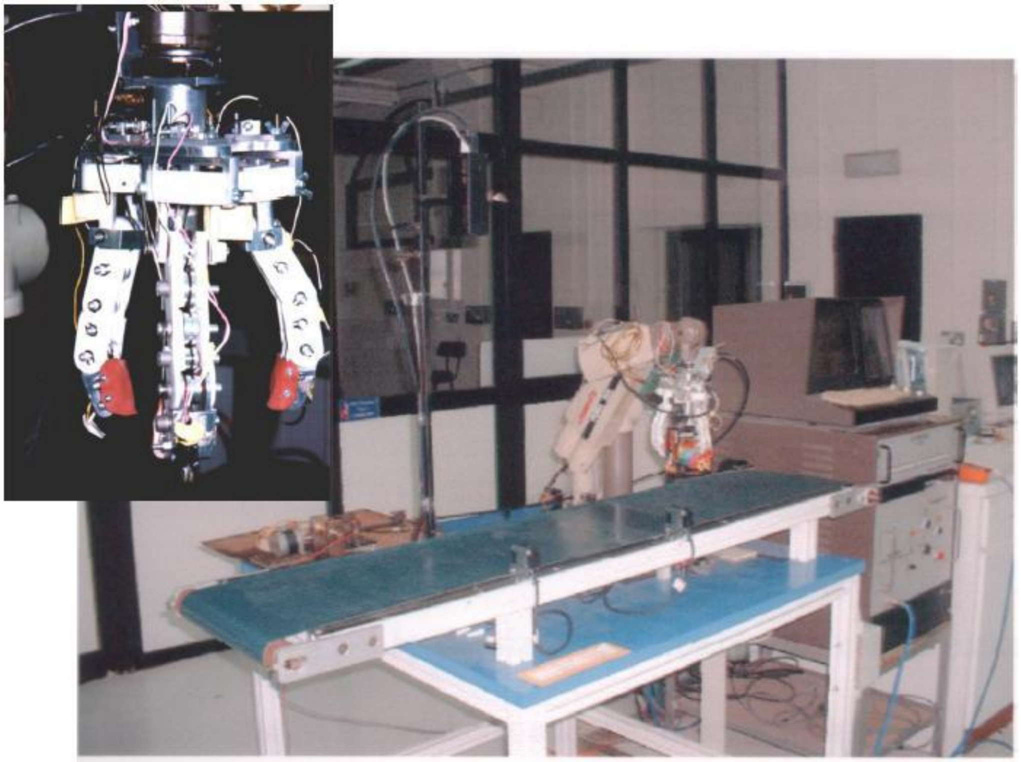


Fig. 1.

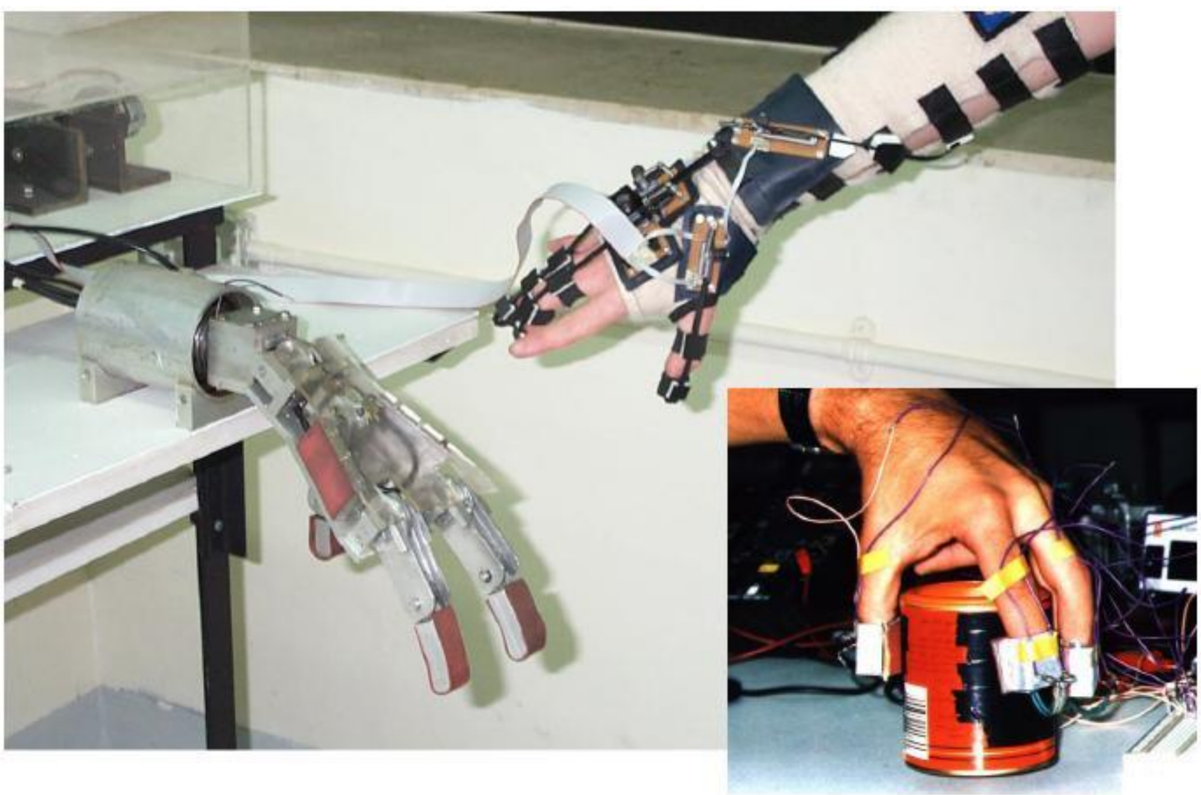


Fig. 2.

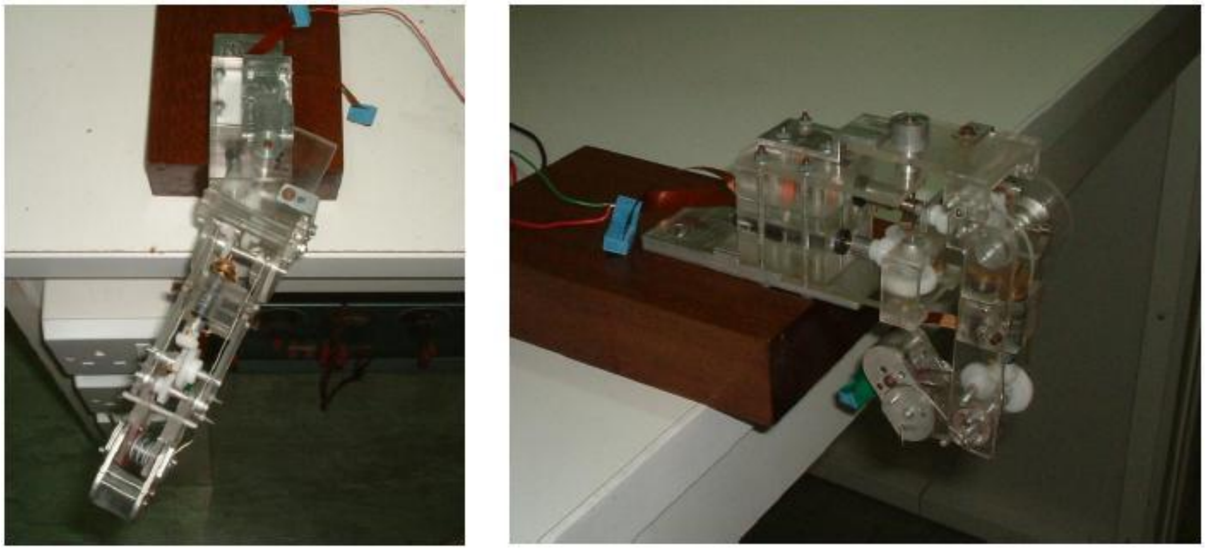


Fig. 3.

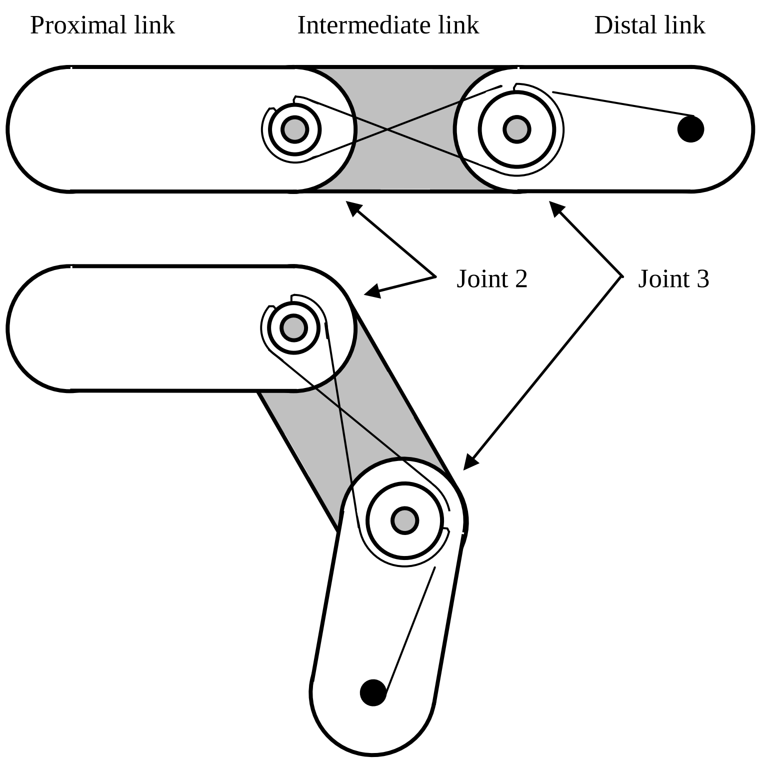

Proximal link
Intermediate link
Distal link
Joint 2
Joint 3

Fig. 4.

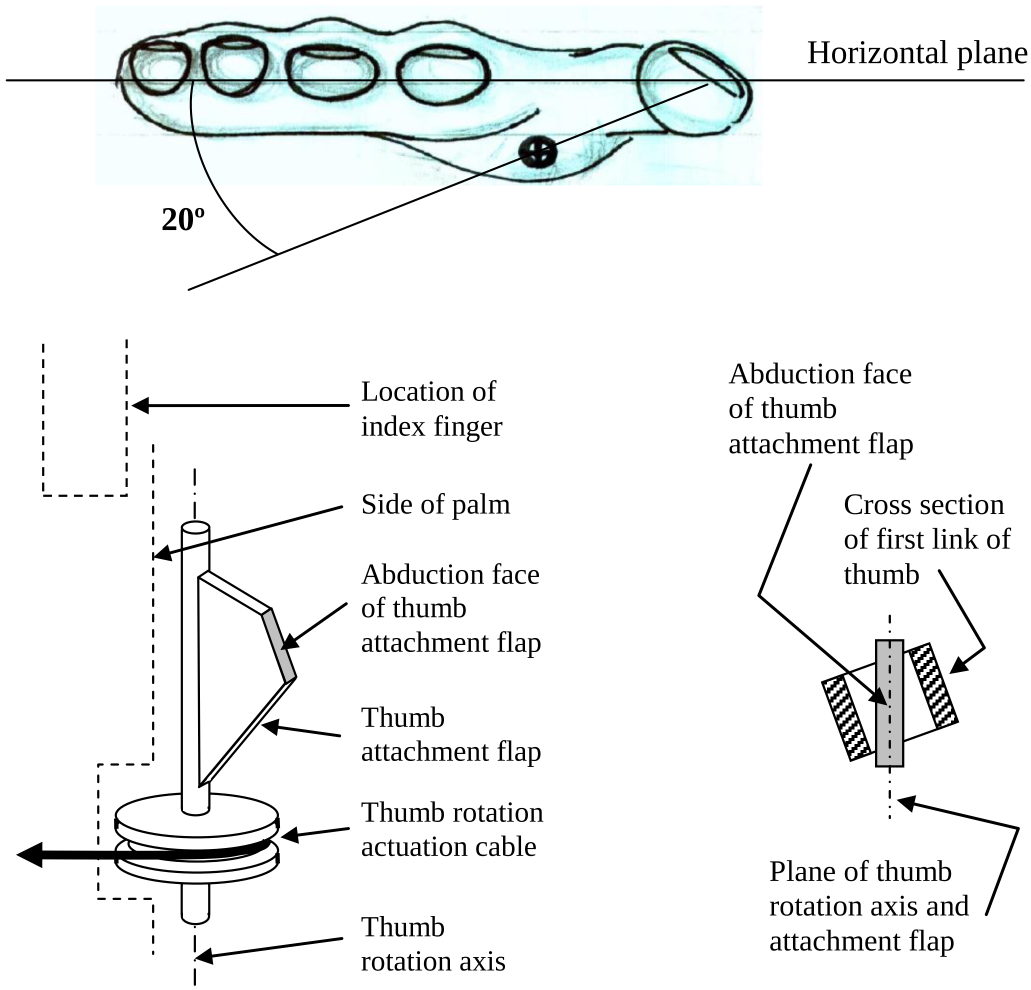

Horizontal plane
20º
Location of index finger
Side of palm
Abduction face of thumb attachment flap
Thumb attachment flap
Thumb rotation actuation cable
Thumb rotation axis
Abduction face of thumb attachment flap
Cross section of first link of thumb
Plane of thumb rotation axis and attachment flap

Fig. 5.

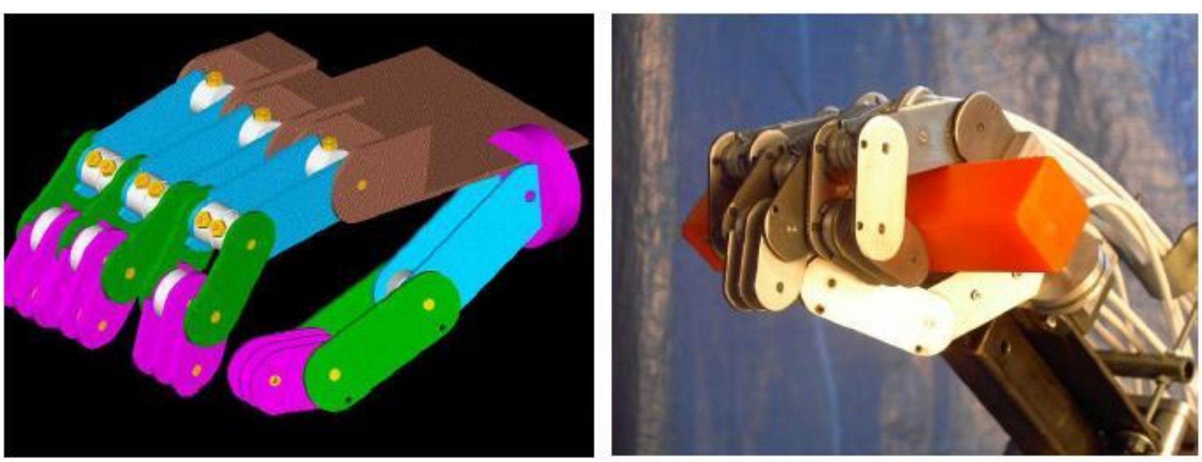


Fig. 6.

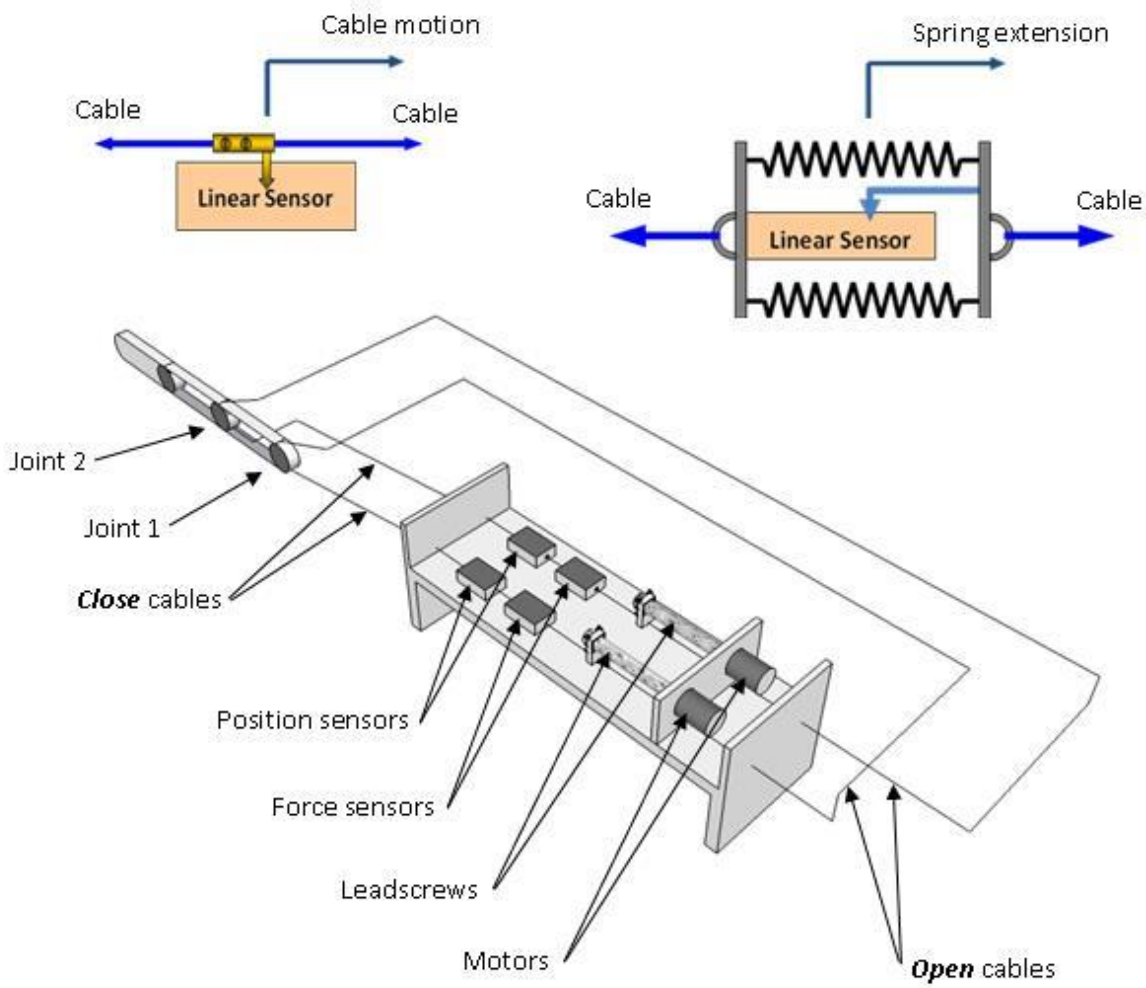

Cable motion
Cable
Cable
Linear Sensor
Spring extension
Cable
Cable
Linear Sensor
Joint 2
Joint 1
Close cables
Position sensors
Force sensors
Leadscrews
Motors
Open cables

Fig. 7.

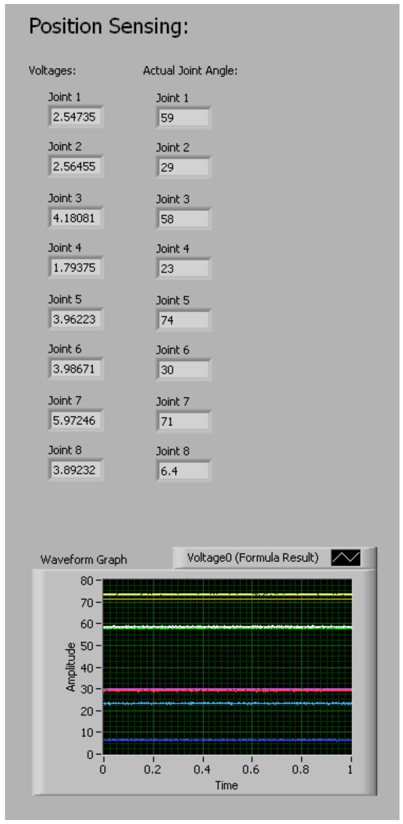

Position Sensing:
Voltages:
Actual Joint Angle:
Joint 1
2.54735
Joint 1
59
Joint 2
2.56455
Joint 2
29
Joint 3
4.18081
Joint 3
58
Joint 4
1.79375
Joint 4
23
Joint 5
3.96223
Joint 5
74
Joint 6
3.98671
Joint 6
30
Joint 7
5.97246
Joint 7
71
Joint 8
3.89232
Joint 8
6.4
Waveform Graph
Voltage0 (Formula Result)
Amplitude
80 70 60 50 40 30 20 10 0
0 0.2 0.4 0.6 0.8 1
Time

Fig. 8.

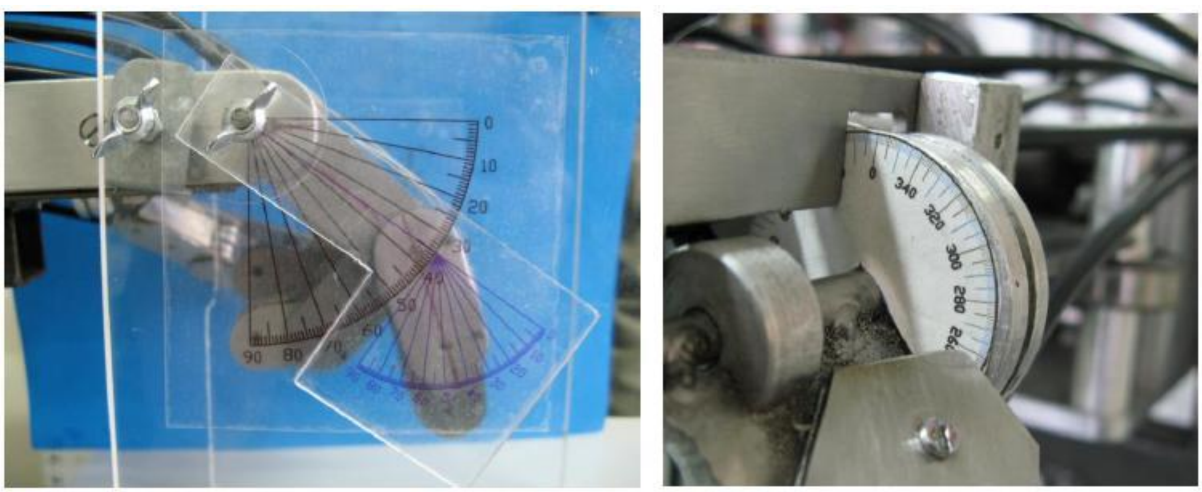
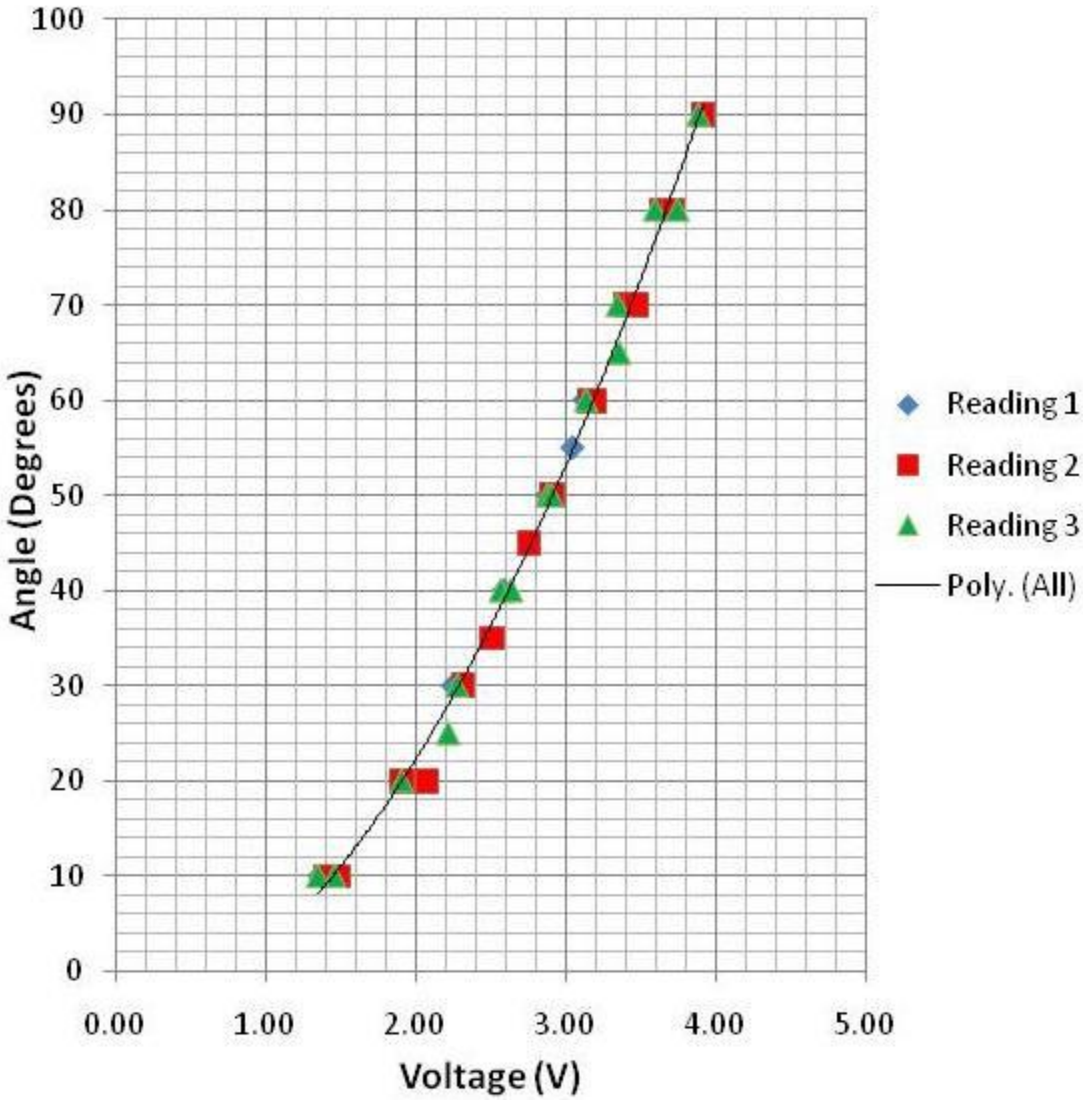


Fig. 9.



100
90
80
70
60
50
40
30
20
10
0
Angle (Degrees)
0.00
1.00
2.00
3.00
4.00
5.00
Voltage (V)
Reading 1
Reading 2
Reading 3
Poly. (All)

Fig. 10.

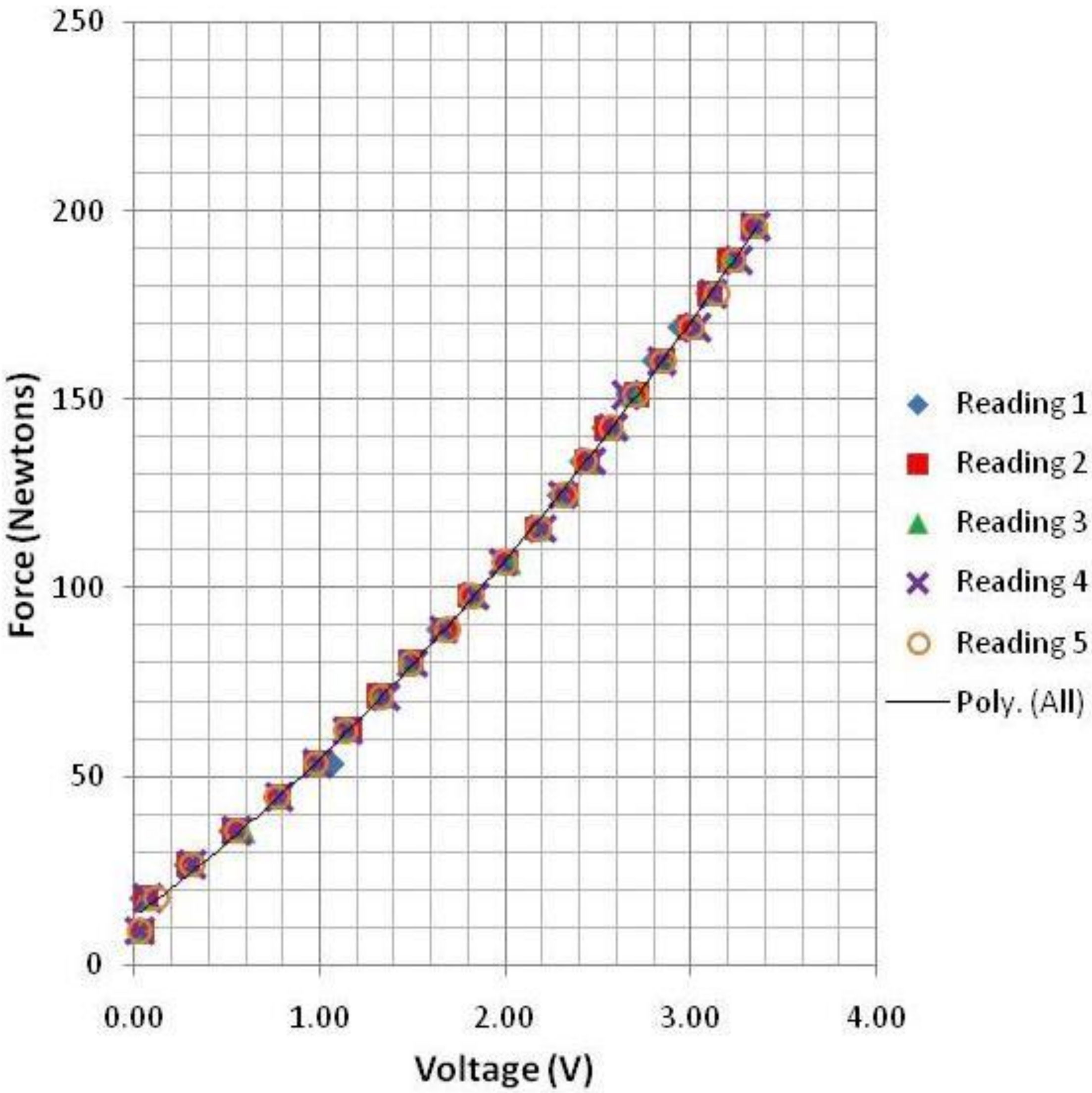

250
200
150
100
50
0
Force (Newtons)
0.00
1.00
2.00
3.00
4.00
Voltage (V)
Reading 1
Reading 2
Reading 3
Reading 4
Reading 5
Poly. (All)

Fig. 11