A Compact Glove Input Device to Measure Human Hand, Wrist and Forearm Joint Positions for Teleoperation Applications

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Abstract—**In this work, we have developed a new glove input device that is able to measure the angular joint positions of two fingers and of the thumb on the human hand, as well as the pitch position of the wrist and the roll position of the radio-ulnar joint of the human forearm. The glove has various new features, including the measurement of forearm roll position, that are not found in other glove input devices described in the literature. The glove contains a number of flexible, plastic bands whose displacement, during joint rotation, is measured using linear potentiometers. The new glove is light, compact, easy to wear and use, robust, and inexpensive, and is intended for use in teleoperation applications in conjunction with a remotely located robot hand/wrist. Another property is that it can be easily adjusted to fit a wide range of human hand sizes. Preliminary testing of the glove has shown that it can achieve an accuracy in position measurement that compares well to that of a number of commercially-produced gloves that are presently in use.**

Keywords—glove input device; whole hand input device; teleoperation; human joint position sensing.

I. INTRODUCTION

The development of data gloves, or whole hand input devices, for the sensing of human hand and wrist movements, is an area that has received a fair amount of attention over the last twenty five years. One of the major commercial exponents of this line of research and technology has been the entertainment industry, specifically in the area of Virtual Reality (VR), where the use of a whole hand input device allows the user to experience a more transparent interaction with a computer-generated environment. However, data gloves also have a number of other very compelling applications outside of VR. These include, for example, the teleoperation of multi degree-of-freedom anthropomorphic robot hands for use in remote and/or hazardous environments; the programming of complex human-type hand motion sequences for autonomous, dexterous robot hand applications, such as for material handling in industry; the implementation of "point, reach, and grab" commands in a gestural interface; and the interpretation of human hand gestures for use by the vocally impaired.

The very earliest data gloves were designed to replace the keyboard as a text input device. These involved fitting the human hand into or against a glove-like device, such that the thumb and each finger could be used to activate a unique switch, and the five signals were used to encode the various character symbols [1] [2]. The gloves in [3] were fitted with electrical contacts on the fingertips, and were designed to work in conjunction with a modified keyboard, fitted with exposed electrical contacts on the upper surface of the keys, as an educational device for teaching touch typing skills.

Possibly the earliest whole hand input device with generic applications was the digital data entry glove in [4]. This glove was intended both as a substitute for the keyboard and mouse for character and command entry into a standard computer, as well as for the interpretation of hand positions representing the Single Hand Manual Alphabet used by the vocally/aurally impaired. The glove comprised a number of touch/proximity sensors (to detect contact between the fingers, or between the fingers and the palm), a number of "knuckle-bend" sensors (to detect flexing of specific hand joints), a number of tilt sensors (to detect hand tilt through the horizontal plane), and a number of inertial sensors (to detect hand acceleration in two orthogonal directions). Each of the sensors gave a two-state output, so that the interpretation of a hand gesture involved the logical decoding of the specific combinations of the digital output signals.

The first commercial glove input device was the VPL DataGlove, developed by VPL Research Inc. [5]. This glove utilizes various sensor technologies, including ten fibre-optic cables that pass over the first two joints of each of the five digits of the human hand, and that exhibit reduced light transmission when they bend, as a function of joint angle [6]. Evaluations of the performance of the VPL DataGlove show the mean error in the sensed position of the fingers to be about 6 degrees (that of the thumb is substantially higher) [7] [8]. A more recent commercial glove input device is the CyberGlove by Immersion Corporation, which uses up to twenty two resistive bend sensors to measure the angular position of the joints of the hand [9]. An evaluation of the glove [10] showed sensor accuracy to be considerably better than that of the VPL DataGlove, with errors of only a few degrees for most of the joints, and with the thumb joints once again displaying the greatest errors.

Various other glove input devices have been developed in recent years, utilizing different technologies for the sensing of finger joint positions. The TU-Berlin SensorGlove [11], for example, used ten inductive length encoders to measure finger flexion and thumb rotation, while the Exos Dexterous Hand Master [12] utilized a number of Hall effect sensors mounted on an exoskeleton to measure twenty degrees-of-freedom on the human fingers and thumb. Many recent gloves have focused more on providing force feedback to the user [13] [14] [15]. The accuracy in joint position measurement of some of these devices is less that 1^{o} (e.g. [14]). Many of these devices however still have a number of shortcomings, such as large size or weight, limited conformity to different sized hands, and/or high cost. In particular, the authors of this paper are not aware of any glove input device that measures the roll position of the forearm.

II. Functions and Attributes of the Device

A. *Required Specifications*

In this work we set out to achieve a number of general objectives for a new glove input device, in order to carry out a preliminary investigation into whether some of the shortcomings of the existing gloves could be addressed effectively. The first of these objectives was for the glove to measure parameters pertaining to both the hand (finger and thumb angular positions) and the wrist, in particular the wrist roll angular position. The second general objective was to develop a glove that could fit a wide range of human hand sizes with only minor adjustments. We required the glove to be robust, but also to be as lightweight and slim as possible, and to minimize interference with the normal hand functions. An overall requirement was to develop a glove that utilized components that were as inexpensive as possible, while maintaining an acceptable degree of accuracy.

The specific features of the new glove input device in its present configuration were determined by its shorter-term applications in our laboratory. We required a glove that could be used to control, through teleoperation, an anthropomorphic robot hand that we had developed earlier. This robot hand had five degrees of freedom, namely the angular motion of the middle and ring fingers and of the thumb, and wrist pitch and roll. The joints within each finger of the robot hand, and within the thumb, were coupled so that each digit effectively had a single degree of freedom in its motion. We therefore required the glove input device to measure the five analogous angular motions of the human hand.

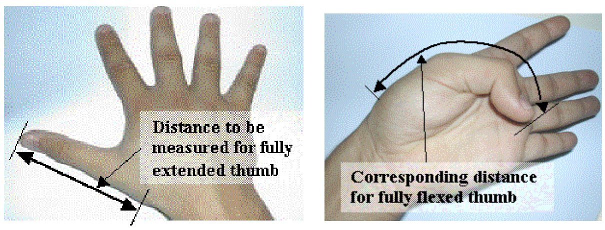
B. *Conceptual Approach*

For the purpose of this work, we defined the angular positions of the fingers of the human hand in terms of the degree to which each finger was curled. In Fig. 1, for example, both the middle and ring fingers are shown in the fully flexed, or fully curled, position, and for each finger this state corresponded to the maximum value of the angular position. It was possible to determine this angular position for each finger by measuring the linear displacement of the free end of a flexible, non-elastic band that was fixed with respect to the fingertip, and that passed along the back of the finger and past the knuckle, towards a fixed datum location on the back of the hand. The same method was used to measure the angular position of the thumb. Fig. 2(a) shows the linear distance between the tip of the thumb and the fixed datum, measured along the back side of the digit with the thumb in the fully extended or uncurled position. In Fig. 2(b) the thumb is shown in the fully flexed, or curled, position, with a corresponding increase in this linear distance.

A similar approach was used to measure the pitch angle of the hand about the wrist joint. Fig. 3 shows a flexible band representing the distance between two datum locations on the back of the hand and of the wrist. As the hand is moved downwards, increasing the pitch angle, the length of this band would need to increase, and this change could be measured as a linear displacement of one end of the band, corresponding to the pitch angle of the wrist.

The most challenging measurement that needed to be taken was that of the roll position of the hand, since in the human this position is changed through a rotation of the entire forearm about the radio-ulnar joint. Nevertheless this measurement could still be accomplished using an approach similar to the above. The rear segment of the glove was extended along the forearm to reach to just below the elbow, and the optimum locations of the fixed datum points, between which to take the linear measurements that would correspond to the roll position, were found through experimentation.

Figure 1. Middle and ring fingers in fully curled positions.



(a) (b)

Figure 2. Thumb in (a) fully extended; and (b) fully flexed position.

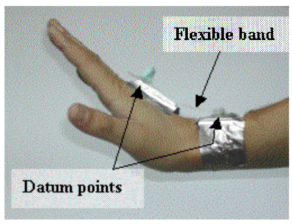
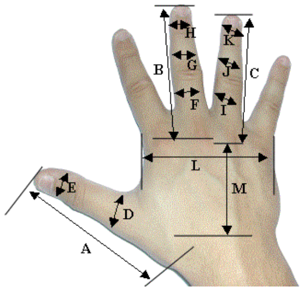


Figure 3. Sensing of pitch angle (concept).

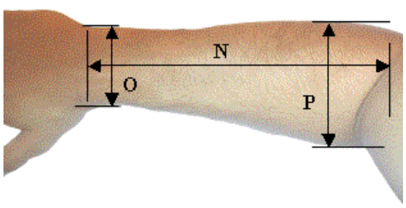
Our requirement for the glove to fit hands of different sizes was addressed by designing the glove to have an open style of architecture. In this way the user would not fit his or her hand into a conventional closed-type glove, but rather the glove would be fitted over and around the user's hand, and the required adjustments for size would then be made. Only a portion of the hand would be enclosed by the glove, and in particular, the glove consisted of two main parts – a lower part that fitted over the hand from below the wrist, and an upper part that fitted around the forearm from above the wrist. The two parts were joined together at the back of the wrist, underneath the pitch-sensing band shown in Fig. 3. In order to determine the range of adjustment that needed to be accommodated by the glove, a series of measurements were taken of the relevant dimensions of the human hand. The measurements were taken over a sample of fifteen adults of different genders.

III. Measurement of Human Hand Parameters

The dimensions that were measured for the human hand and forearm are shown in Fig. 4(a) and Fig. 4(b), and the results are summarized in Table I. All measurements were taken using a flexible measuring tape. Following the static measurements, a number of measurements of *extension due to joint rotation* were taken as described below.



(a)



(b)

Figure 4. The dimensions measured for the (a) hand, and (b) forearm.

A. Middle and Ring Fingers

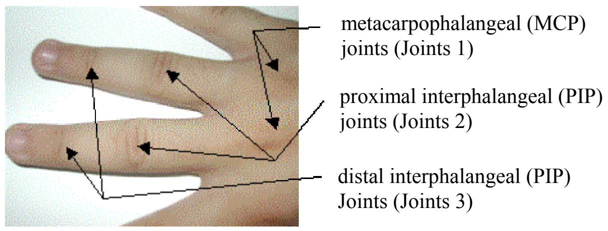
Fig. 5(a) shows the middle and ring fingers in the extended positions. In the human finger, joints 2 and 3 are coupled, and constitute collectively one degree-of-freedom. Joint 1 has two degrees-of-freedom (finger pitch and yaw). For the reason cited in section IIA the yaw of joints 1 were not measured, and moreover joints 1, 2 and 3 were considered to be one degree-of-freedom, with extension measurements taken collectively over these joints for each human finger. This simplification does not have a major impact on the general performance of the glove, as will be discussed in section VI. For each finger, and for each person, the distance between the back of the knuckle and the fingertip was measured along the back of the finger using a flexible measuring tape, first with the finger in the extended position (as in Fig. 5(a)) and then with the finger in the fully curled position (Fig. 1).

TABLE I. DIMENSION MEASUREMENTS OF THE HUMAN HAND

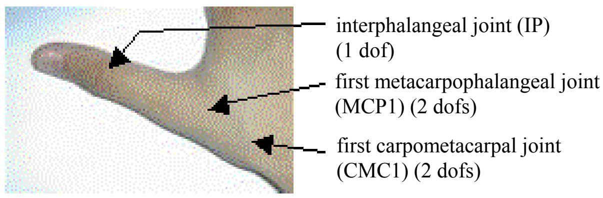
Gender	Age	Dimension (mm)															
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*
male	22	118	122	116	21	19	20	17	18	20	18	16	96	71	217	56	87
male	22	119	117	114	23	21	21	23	20	21	22	18	94	75	206	61	84
male	21	117	118	113	18	17	21	22	19	18	19	18	92	71	208	46	79
male	20	119	124	119	22	24	19	20	18	19	20	19	93	74	214	44	85
female	20	118	117	112	23	21	21	22	17	18	20	16	90	72	214	52	74
female	21	117	122	117	22	18	19	20	18	18	18	16	81	69	235	55	76
female	22	110	117	113	21	20	19	21	17	16	19	17	96	79	218	50	79
male	23	129	130	126	26	22	22	25	20	23	24	19	101	82	258	58	98
female	21	116	118	112	21	20	18	20	18	18	19	17	89	75	221	56	87
male	24	118	121	116	23	19	22	21	17	20	18	16	87	77	237	52	84
male	22	124	125	122	26	21	22	23	16	22	20	16	96	76	241	61	76
female	21	114	122	119	22	20	21	21	18	17	17	16	83	74	226	52	91
female	20	110	117	111	21	18	20	20	16	21	21	15	79	74	214	50	93
male	23	120	123	118	20	19	23	24	18	21	20	18	88	81	241	56	95
male	23	122	116	110	22	18	19	18	15	18	16	17	96	80	254	53	90
AVERAGE:		**118**	**121**	**116**	**22**	**20**	**20**	**21**	**18**	**19**	**19**	**17**	**91**	**75**	**227**	**53**	**85**

B. Thumb

The human thumb has five degrees-of-freedom, shown in Fig. 5(b), however in this work only the pitch-type motions of the three joints were considered, taken collectively as one degree-of-freedom as in the case of the fingers. The distance between the fixed datum and the tip of the thumb was measured for the fully extended and fully flexed positions shown in Fig. 2(a) and Fig. 2(b).



(a)



(b)

Figure 5. (a) Middle and ring fingers, and (b) thumb, shown in extended positions.

C. Wrist Pitch

The applicable extension for the pitch joint of the wrist was taken to be the difference between the length of a flexible band for a pitch angle of –45° (as shown in Fig. 3), and the length of the band for a pitch angle of +45°.

D. Hand Roll

The best locations for the fixed datum points that were needed for the measurement of hand roll were found to be (i) a location just below and on the outside of the elbow, and (ii) a location just above the back of the wrist, as shown in Fig. 6. The flexible band that was used to measure the roll of the radio-ulnar joint would be routed from the first of these two locations down and around the forearm in a three-quarter turn to the second location, as illustrated in the figure. The applicable extension for the roll joint that was measured was therefore the difference in length of this path, for the hand in two extreme positions of roll, i.e. at 0^o (palm down) and at 180^o (palm up). It is to be noted that this specific path was not the path that showed the largest extension during the hand roll, however it was the most convenient path when taking into consideration other factors such as the linear displacement sensor that was selected and its location on the forearm.

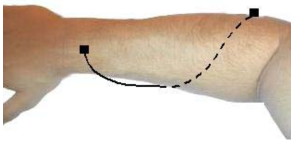


Figure 6. Contour that was measured for hand roll.

E. *Summary of extension measurements*

A summary of the extension measurements is given in Table II. These measurements were taken over a sample of five adults of different genders. In Table II, L_1 and L_2 represent linear measurements taken at the two extreme values of angular joint position, and E is the extension given by $L_2 - L_1$. All dimensions in the table are in mm.

TABLE II. EXTENSION MEASUREMENTS OF THE HUMAN HAND

Gender	Thumb			Middle Finger			Ring Finger			Wrist Pitch			Forearm Roll		
	L_1	L_2	E	L_1	L_2	E	L_1	L_2	E	L_1	L_2	E	L_1	L_2	E
male	76	90	14	129	156	27	124	152	28	61	80	19	325	352	27
female	58	70	12	100	126	26	96	124	28	59	76	17	280	309	28
male	65	79	14	101	125	24	91	116	25	64	78	24	291	320	29
male	72	83	11	111	140	29	102	130	28	56	80	24	327	350	23
female	62	74	12	106	131	25	99	127	28	52	79	27	287	311	24

IV. DESIGN AND FABRICATION OF THE GLOVE

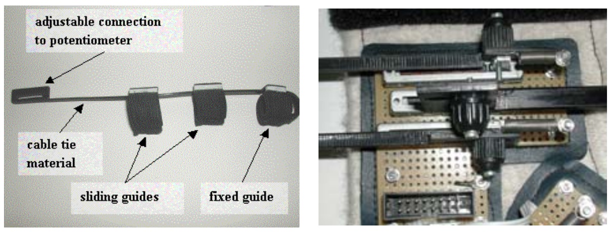
The new glove was designed based on the data that were measured in section III. A systematic approach was taken to the design process, taking into account factors such as required performance, projected service life, serviceability, size and weight, target cost, ease of manufacture, availability of manufacturing facilities and of materials, aesthetics, ergonomics, and safety of use. A morphological chart was drawn up to evaluate the various options that were available for each of the main functions and components of the glove such as displacement measurement, joining of the sub-components, linkage mechanisms, return mechanisms, main structure of the glove, and interfacing with the PC.

The sensor that was selected for the displacement measurement was the dual carbon track linear potentiometer, and we attached helical springs to these sensors as a return mechanism. The required stiffness of these return springs were measured through experiment, and were found to be about 0.06 N/mm for the middle and ring fingers and for the hand roll, and about 0.09 N/mm for the thumb. The wrist pitch sensor did not require a return mechanism. These low-stiffness springs did not impede normal motion of the hand. Linkages on the glove were achieved using flexible, non-elastic bands discussed in section IIB – in the prototype we used plastic material cut from cable ties, with incorporated settings to adjust for hands of different sizes. These bands were routed through guiding channels whose locations could be adjusted on the glove. The linkage mechanism for the ring finger is shown in Fig. 7(a).

The base material used for the main structure of the glove was a tri-tension elastic fabric, and the glove was closed around the hand and forearm using Velcro® ties. The sensor mechanisms were mounted onto strips of veroboard that were attached using screws to leather platforms sewn onto the fabric (see Fig. 7(b)).

The electrical circuit used for each potentiometer is shown in Fig. 8. Each circuit produced an analogue voltage output that corresponded to the angular position of the appropriate human joint. Whenever the glove was utilized by a new user, it was important to carry out a calibration procedure for each of the five degrees-of-freedom, in order to match the range of motion of the potentiometer to the required output voltage range. This was done using a 1KΩ multi turn variable resistor that was incorporated into the circuit as shown in the figure.

The glove in open and closed configurations is shown in Fig. 9. The glove can be fitted onto the hand through a relatively simple procedure, which may take a few minutes if linkage range adjustments have to be made for a new user. The calibration procedure likewise can be done in a few minutes. In our application, the analogue outputs from the glove were fed into a data acquisition card installed on a PC, and the calibration procedure was carried out with the aid of software written specifically for this purpose. During the calibration, the user was required to move each of the five measured degrees-of-freedom of his/her hand, wrist and forearm to the two extreme limits of their range.



(a) (b)

Figure 7. (a) Adjustable linkage for ring finger; and (b) sensor attachment to glove.

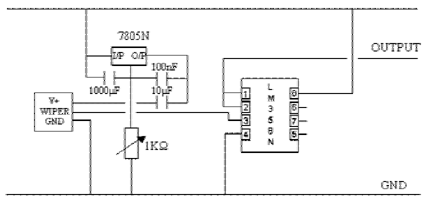
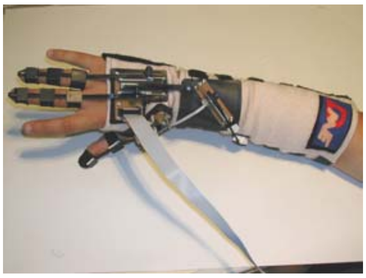


Figure 8. Potentiometer circuitry.

(a)



(b)

Figure 9. The new glove input device, shown (a) open, and (b) closed.

V. Performance Evaluation of the Glove

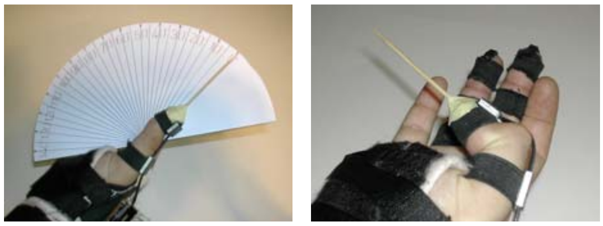
The experimental set-ups used for the preliminary measurements of glove performance are shown in Figs. 10 to 12. In each case the analogue voltage output from the potentiometer circuitry was measured as a function of angular position of the relevant degree-of-freedom, and each test was repeated several times. The experimental results are given in Fig. 13. The results indicate that there is very good repeatability of the position readings for all the joints being measured. In addition, the wrist and forearm measurements displayed very good linearity and indicate that accuracies of the order of about 2^o may be achievable without the need for non-linear curve fitting for these two joints. The preliminary results compare well to those of the more popular commercial gloves that are presently in use, discussed in section I. In particular, a very good result has been obtained for the sensing of roll joint position, which is one of the main new features of this glove.

VI. Conclusion

In this work, we have designed, constructed and demonstrated a new glove input device that is light and easy to use, and that can be produced in a relatively inexpensive manner. The glove can be fitted easily to different hand sizes, and measures information pertaining to the hand (two fingers and thumb), the wrist and the forearm. Preliminary tests have indicated good accuracy of joint position measurement using the new glove.

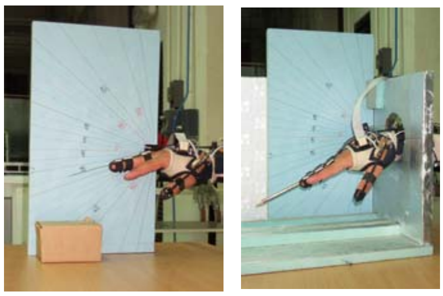
The present version of the glove is intended mainly to test a number of new and specific concepts in the sensing of hand, wrist and forearm joint positions, and as such certain measurements that may be desirable in a more complete whole hand input device are not yet supported. In particular, position measurement of the index and little fingers is omitted, and moreover, the angular positions of the middle and ring fingers, and of the thumb, are measured as a single degree-of-freedom in each case. The latter limitation means that presently the glove does not differentiate between motion of the independent joints of each human digit, but rather gives a single angular position reading for each digit, which is a measure of the amount of total curl of the digit. This information, however, is already sufficient for a wide range of teleoperation applications, particularly in cases where there is visual feedback of the robot hand. Fig. 14 shows the glove in use with the anthropomorphic robot hand in the Industrial Automation Laboratory at the University of Malta.

Future work in this area will focus on more extensive testing of the glove using more than one human subject. In particular, if the shape of the characteristic curves illustrated in Figs. 13(a), (b) and (c) are found to be typical for the majority of users, then a further improved accuracy of the glove for the finger and thumb joints can be obtained based on non-linear fits to the empirical test results. Future versions of the glove will focus on incorporating the index finger, and on measuring the positions of the individual finger joints. Modification of the glove to provide haptic feedback to the user is also under consideration.



(a) (b)

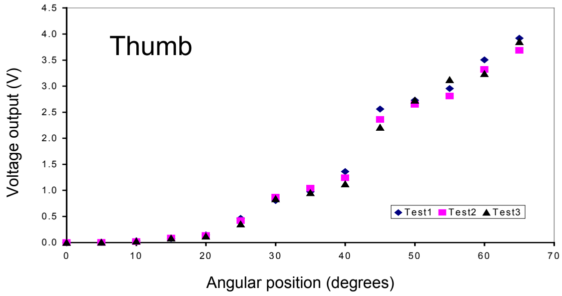
Figure 10. Testing of angular position measurement for thumb, (a) fully extended, and (b) fully flexed (position template not shown).



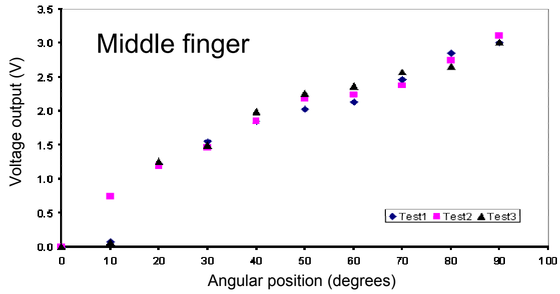
(a) (b)

Figure 11. Testing of angular position measurement for (a) middle finger (ring finger was measured using a similar procedure), and (b) wrist pitch.

Figure 12. Testing of angular position measurement for forearm roll.



(a)



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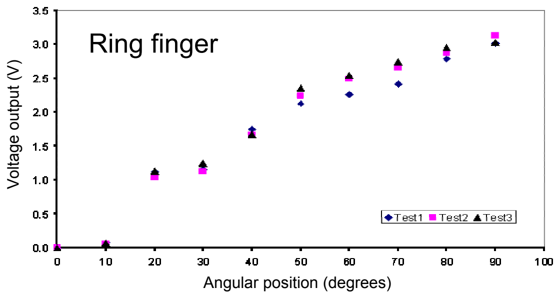

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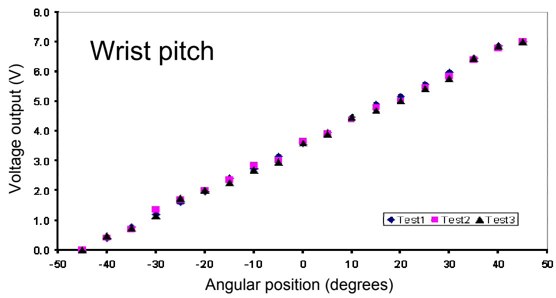
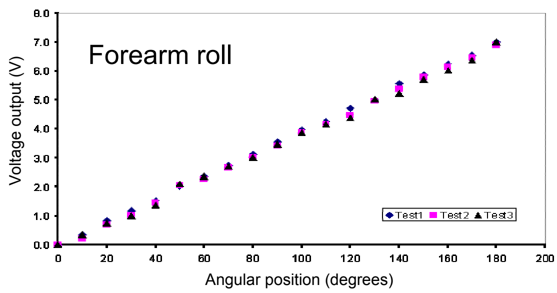


(d)



(e)

Figure 13. Experimental results

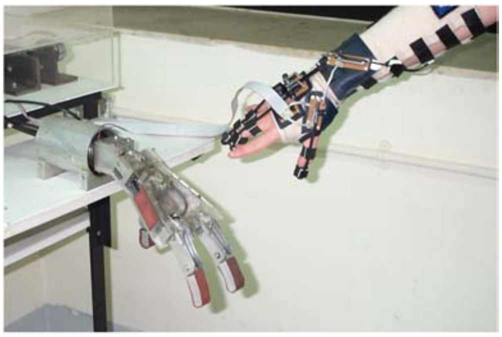


Figure 14. The glove input device, shown together with the teleoperated anthropomorphic robot hand [16] in the Industrial Automation Laboratory of the Department of Manufacturing Engineering at the University of Malta.

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