DESIGN AND DEVELOPMENT OF A LOW-COST WIRELESS DATA GLOVE FOR REMOTE ROBOTIC HAND OPERATION

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ABSTRACT  
The goal of this project is to develop a teleoperated robotic hand with an emphasis on minimizing cost. Traditionally, use of low-cost sensors meant a sacrifice in the positional accuracy of the finger joints due to noise and high degree of nonlinearity. External vision systems provide accurate data, but suffer from being limited to specific lighting conditions and are hardly mobile. We have developed a robust data glove with a wireless connectivity to a nearby PC that is networked to a robotic arm in the different laboratory through a wireless LAN. In its prototype stage, each finger is modeled as a single joint. To measure the relative angular displacement of each joint, a hollow transparent polyurethane tube is attached along the length of each finger. An Infrared LED and a matched phototransistor are attached at the opposite ends of each tube. The bending of each finger proportionally diminishes the intensity of the light seen by the phototransistor, as a fraction of emitted energy escapes through the bend of the transparent tube. To filter the affects of external lighting and mains coupling each IR source is modulated at different frequencies to prevent interference between the signals. The relationship between relative angular displacement and the sensor signal is a highly nonlinear function that we have linearized through a combination of a non-linear amplifier and a digital look-up-table (LUT). The LUT is generated by custom-designed computer vision software that fits the true angular displacements to the function generated by passing the signal through a non-linear amplifier stage. A low-cost onboard 8-bit microcontroller applies the stored LUT to the digitized measurements from the sensors. The 16-bit positional values are then transmitted by a UDP (Universal Data Protocol) to the client PC that outputs motor commands to the servos in the robotic hand. Positional accuracy, noise and linearity were then analyzed by the same machine vision software and its effectiveness compared to the pure machine vision approach.

1 INTRODUCTION  
1.1 Overview of current technology  
A majority of commercial data-gloves today are designed for a virtual reality interface. As such, they require additional calibration or modification for interfacing with a robotic hand. Such interfaces find important use in studies involving man-machine systems, rehabilitation and remote operation of robotic devices in distant or hazardous environments. The main components of such system are: joint angle-measuring sensors, signal processing electronics, communications interface and a robotic hand. This paper describes the synthesis of such system with an emphasis on minimizing cost of sensors, while maintaining accuracy and linearity of motion control. Traditionally, the largest cost element in data-gloves has been the joint angle-measuring sensors [3]. During the last two decades, several different designs have been proposed and implemented. Fifth Dimensions Technologies (5DT, Irvine, CA) produce a 16-sensor wireless data-glove that utilizes fiber-optic sensors to measure joint positions. While producing exceptional results with repeatability, the cost of the glove is prohibitively expensive (>5,000 USD). The Essential Reality (Mineola, NY) P5 glove implements resistive flex sensors for flexion measurements manufactured by Abrams/Gentile. However, such sensors are inadequate for control of a robotic hand as they exhibit hysteresis during repetitive motion. [3] Lisa K Simone et al have been able to solve the problem by removing a protective coating from the sensor. However this leads to deterioration of the sensor’s surface and produces errors in the subsequent measurements [3]. Machine vision approach circumvents the problems of the aforementioned sensors by implementing algorithms to track markers on the user’s data glove. Because the glove requires no electronic components, power supply or sensors, it is extremely lightweight and suitable for prolonged wear. In addition, the approach measures joint angles directly and is
thus linear in its nature. However, the main limitation to this approach is its immobility and inherent dependence on good lighting conditions and uncluttered background. Cristina Manresa et al have implemented a more robust algorithm for hand gesture recognition. Although relatively immune to background clutter and noise, the approach is unsuitable for a low-cost control of a robotic hand, as it is limited to a discrete set of gestures and is incapable of continuous tracking of joint angles [1].

1.2 System Overview

Three primary components comprise the man-machine hand interface: self-powered, wireless data glove as an input device, server-client network interface and a robotic hand as an output device. Initial design and prototyping was performed in the same lab with two PCs connected through a wireless LAN. A user wearing the data glove establishes a Bluetooth serial link with the host PC. All signal processing electronics is enclosed in the base of the glove (Fig. 2C). Upon reception of the Bluetooth packets by the server PC, the serial stream is forwarded through the network via a connectionless protocol (UDP) to the client PC. The client PC is connected serially to the robotic hand (Fig. 4B) through the LYNX© servo controller (Fig. 4A) which directly drives the joint actuators.

![Image](figure1.jpg)

**Figure 1.** Man-machine system overview

1.2.1 Data-Glove

The largest fraction of cost in any data-glove is contributed by the joint angle-measuring sensors. Most commercially available low-cost sensors exhibit hysteresis and are thus inadequate for a purpose of motion control. As a result, this research has concentrated on developing a durable, low-cost sensor for measuring joint angles that is comparable to accuracy and durability of the expensive fiber-optic sensors implemented by Fifth Dimensions Technologies©. The developed sensor works on the principle of measuring the change in light intensity generated by an Infrared LED at one end of a hollow, transparent polyurethane tube (Fig. 3A). As the tube is bent along its longitudinal axis, a fraction of emitted light escapes through the transparent sheath, thereby reducing the received energy at the opposite end of the tube. A phototransistor is mounted at the receiving end to measure the intensity of the Infrared light (Fig. 3B). The relationship between phototransistor output and bend angle constitutes the joint angle-measuring system. Although DataGlove© by 5DT utilizes similar principle, the use of fiber-optic cable requires expensive emitter and transducer couplings as well as specialized optical filtering that is absent from our design [4]. As a result, the developed sensor consists only of a matched off-the-shelf IR LED and phototransistor, dramatically reducing cost and simplifying hardware design. However, because of the lack of optical filtering, our sensor requires additional analog and digital filtering stages to remove the optical noise. In addition, because of the relatively large radius of the sensor (5.0mm), the output of the phototransistor is not linearly related to the bend angle of the sensor. Filtering, linearization and calibration processes are the central focus of our research in designing these sensors. Our initial prototype implements four sensors mounted along the long axis of each finger (excluding the thumb). One sensor is used per each finger for evaluation, although for a final prototype the number of sensors can be increased.

![Image](figure2.jpg)

**Figure 2.** Completed data-glove prototype

![Image](figure3.jpg)

**Figure 3.** Joint angle-measuring sensors

1.2.2 Networking

To permit freedom of motion, Bluetooth connectivity between the host PC and the data-glove is established. The processed data from the angular sensors is a 16-bit value sampled by the on-board Microchip© MCP3553 Analog to Digital Converter. Digitized signal is then transmitted through SPI to the Microchip© PIC-18F2520 microcontroller (Fig. 2C) and sent through UART to the AirCABLE© module attached to the serial port. (Fig. 2B). The serial stream is received by the Host PC nearby and forwarded through the network via a UDP protocol to the client PC interfaced to the Robotic Hand.
1.2.3 Robotic Hand

The robotic hand prototype (Fig. 4B, developed by Eli Worden of City College) features five servo motors with direct linkages to the fingers. Each finger is connected by an antagonistic pair of cables to the respective servo motor allowing bidirectional control. Each servo is controlled independently by the client PC by sending a command string of 16-bit values corresponding to the angular position of each finger to the LYNX© servo controller (Fig. 4A).

![Figure 4](image)

Figure 4 Robotic Hand setup with servo controller

2 SENSOR CONDITIONING

2.1 Evaluation of single-joint actuation

In our initial prototype, each finger is approximated by a single joint. Anatomy of a human finger (Fig. 5) consists of three segments – the tip, middle and base segments (distal, middle and proximal phalanges respectively). With the exception of a first joint (between the base knuckle and the proximal phalanx), each joint has a single degree of freedom. The sensor’s midpoint is mounted above the proximal interphalangeal joint (PIP).

![Figure 5](image)

Figure 5 Finger joints in a human hand

Figure 5 depicts absolute angles ($q_1$, $q_2$, $q_3$) of the base, proximal and distal joints respectively. Anatomically, $q_1$ and $q_2$ are controlled independently and $q_3$ and $q_1$ are holomorphically constrained [2]. Although independent control over $q_1$ and $q_2$ is required for complete dexterity, it is important to note that a large subset of finger motion can be simplified to a single variable. Typical grasping motion of cylinders of various radii, for example, can be described by a single variable $\theta$, an angle that vector OP makes with the reference axis. Figure 5 presents three frames that depict a subset of the range of $\theta$. To examine the behavior of $\theta$, we have developed motion analysis software that tracks the designated markers on the data-glove and the robotic hand. Two markers were tracked, one on the tip of the index finger, and the other at the base joint (base knuckle). The frames were captured from the camera at a rate of 10 frame per second, and $\theta$ calculated from the analyzed data. We have found that during typical grasping or fist-making motion of the hand, $\theta$ varies linearly with time (Fig. 6).

![Figure 6](image)

Figure 6 Angle vs. Time during typical grasping motion

Similarly, we have tracked the motion of a robotic finger. The servos were commanded to rotate at a constant angular rate, and the angle $\theta$ was plotted against time. Because the angular rate is more precisely controlled in a servo mechanism, the result also produced a linear relationship between time and angle $\theta$ (Fig 7). This demonstrates that although a human anatomy allows for two independent degrees of freedom in the finger, during a typical grasping motion, the result can be achieved by a single actuator rotating at a constant angular rate.

![Figure 7](image)

Figure 7 Time vs. Angle in Linear actuation of a robotic finger
2.2 Intrinsic Sensor Nonlinearity

Using custom-designed motion-analysis software we have analyzed the relationship of phototransistor output voltage and $\theta$. The relationship is a highly non-linear function that saturates rapidly during the first twenty degrees of bend (Fig. 10). In fact, the output of the transistor is nearly constant past fifty degrees. Because the current output of a phototransistor is very linear with light intensity, the only source of nonlinearity is the refraction of light inside the sensor. To test the direct effect of the sensor output on motor control, we have fed the sensor output while bending a finger at a constant angular rate. The angle of the finger $\theta$ can be seen to rapidly saturate to a closed position (Fig. 11).

2.3 Linearization of Sensor output

Because the output of the phototransistor is a highly nonlinear function with respect to bend angle, we have developed a dual-stage linearization process by combining analog and digital filters to minimize cost and increase efficiency. First, the nonlinear signal passes through an exponential amplifier to minimize the saturation angle and linearize the relationship between transistor output and bend angle. The exponential amplifier, however, is incapable of producing a precise linear function, as its transfer function depends closely on precision of the components, which in turn are highly sensitive to external factors, such as temperature and noise. Therefore, the exponential amplifier acts as a rough linearizer prior to the digital stage. Following the exponential amplifier stage, the signal is digitally sampled and subjected to a look-up-table stored in the microcontroller. The look-up-table is generated experimentally by computing an inverse of the transfer function obtained from the exponential amplifier relation, thus obtaining angle vs. voltage relationship. Careful tuning and calibration of both exponential amplifier and digital look-up-table is critical to obtain maximum precision and linearity during operation.
2.3.1 Exponential Amplifier Stage Design
Without an exponential amplifier, the Analog to Digital conversion stage would be required to have high enough resolution to sample the slowly rising slope during the saturated state of the transistor output where voltage varies within microvolt range. Such a converter would not satisfy the low-cost criteria of the project and add complexity to the analog filtering stage. The exponential amplifier depicted in Figure 12 features two control resistors – a shunt resistor $R_s$ and a feedback resistor $R_f$. The saturation angle of the exponential amplifier can be controlled by varying the ratio between the two resistors. We have performed experimental sweep analysis by varying the ratio of $R_f/R_s$ from 3 to 0.015. The nonlinear transistor output in Figure 10 was subjected to the exponential amplifier. The results are depicted in Figure 13. It can be seen that with larger ratios of $R_f/R_s$, the output of the amplifier becomes highly linear, but saturates rapidly at approximately seventeen degrees of bend. When both resistor values are equal, the output voltage follows the curve of the transistor closely until approximately an inflection point at twenty-five degrees, where it rises to saturation.

![Figure 12. Exponential Amplifier and Signal Buffer](image)

![Figure 13 Output function of the exponential amplifier at different ratios of $R_f/R_s$](image)

2.3.2 Digital Amplifier Stage Design
After experimentally gathering the family of curves depicted in Figure 13, a decision regarding the specific ratio of $R_f/R_s$ had to be made. Two factors influence a specific choice of resistors – nonlinearity and saturation angle. Because any one finger must be allowed a wide-enough range to be able to make a complete fist or grasp an object, the saturation voltage must be above 90 degrees. A second factor influencing a particular choice of $R_f/R_s$ ratio is the degree of nonlinearity the function exhibits. If the nonlinearity is too great, a 16-bit analog-to-digital converter will not be able to measure the shallow slope of a saturation function approaching the asymptote. To determine the best choice of a particular ratio, we have computed the inverse function for each of the curves in Figure 13. The resulting function represents the mapping of voltage to angle that the microcontroller will be required to implement. The mapping is implemented by a look-up-table that contains the pre-calculated values obtained from the inverse relations. After obtaining the inverse relations we have computed their derivative to obtain the rate of change of output signal vs. input voltage. A large slope indicates that the mapping function is changing too rapidly to preserve the desired resolution of the converter. As a result, the effective resolution obtained after the transformation will be less than the resolution of the converter (16 bits). Figure 14 depicts the worst-case resolution for a particular set of $R_f/R_s$. It can be seen that for an unprocessed data (blue) the resolution reduces at the fastest rate, deteriorating to less than 8 bits in the first half of the measured set. After evaluating the data, we have determined to use the resistor ratio of 0.50, which reduces effective resolution to 15.9 bits and allows a maximum range of motion of 90 degrees.

![Figure 14 Effective resolution vs. input voltage at different ratios of $R_f/R_s$](image)

2.4 Noise Removal and Signal Conditioning
The nature of the angle-measuring sensor relies on the transparency of the tube to allow the emitted IR energy to escape through the sheath. As a consequence, a phototransistor is not protected from the external noise, a source of which may be fluorescent and incandescent lighting as well as the changing DC levels when, for example, the finger is moved through a shade. To counteract this deficiency each IR signal is modulated by a square wave produced by a microcontroller. To reduce interference between different phototransistors, the fingers are frequency-multiplexed. Each finger is allotted a 100 Hz bandwidth beginning with the Index finger modulated at 100 Hz. A frequency spectrum depicting the multiplexing technique is illustrated in Figure 15.
The process for filtering and de-multiplexing is illustrated in Figure 16. A raw signal output from the phototransistor is buffered and passed through an active 2-pole bandpass filter of $Q = 20$. The center frequency of the filter is set to the particular frequency to be de-multiplexed and then half-wave rectified. The resulting signal is subjected to a two-stage low-pass RC filter with a cut-off frequency of 10 Hz. A sinusoidal-like motion of an index finger at an approximate frequency of 5 Hz is depicted in time domain in Figure 18, as well as in the frequency domain in Figure 17. Both raw and filtered signals can be observed clearly. A modulated oscillatory movement of the finger can be observed on the frequency spectrum as the sidebands separated by approximately 5 Hz from the 100 Hz carrier. Because of RC filter network, a noticeable phase delay can be observed in the time-domain in Figure 18. The output of the filter is then admitted by the linearization stage discussed above.

### 3 RESULTS

During operation of the system, the user is required to extend the fingers into a palm and then make a fist. The obtained readings are then calibrated with the limit values of the servos and mapped with a 1:1 angle ratio. During the analysis of the system, we have applied the motion analysis software to the user and the robotic hand by two cameras simultaneously. The mapping of the robotic finger $\theta$ to the user finger $\theta_c$ closely resembles a linear relationship (Fig. 19). Figure 20 depicts the motion sequence and angles of the user finger and a robotic finger.
Although the results obtained are promising, several variables have not been completely eliminated from the analysis and require further research. One important issue is the flexibility of the sensor. During our experimentation we assumed that the user would not permit abduction of the proximal phalange. If permitted, the sensor would be allowed to bend perpendicular to its long axis and would thus yield false measurements. Such erroneous readings could also result from the buckling of the sensor after prolonged use. Abduction and sensor dislocation are the main sources of inaccuracies in the obtained results. If properly secured, the readings should improve.

4 CONCLUSION

The goal of this project has been to minimize cost while preserving effectiveness of the design. By introducing low-cost bend sensors we have reduced the cost of the glove dramatically. In consequence, the low-cost components and a wide transparent tube have introduced severe nonlinearities and external noise. Our solution is one that can be applied to other low-cost sensors which intrinsically exhibit nonlinearities and high susceptibility to noise. Where a digital linearization technique alone is inadequate because of limited resolution A/D, we have implemented a two-stage process, where an introduction of circuit non-linearity acts to roughly linearize the output which is then processed by a digital stage. In the process we have utilized custom-designed motion analysis software to perform necessary calibrations. We have shown that a low-cost sensor is capable of producing useful results by carefully tuning a calibration network consisting of analog and digital components. As such, our approach is nevertheless limited. We have only utilized a single sensor per finger, limiting the degree of freedom, although a higher number of sensors can be used in the future. In addition, the inherent flexibility of the sensor allows it to bend in various planes, thus producing discrepancies in readings. To counteract the problem, a specialized hardware mount needs to be developed. Most importantly we have designed the data-glove in regard to the entire system. Such approach inherently matches the data-glove to a specific robotic hand, thus providing the user with a well-matched system for a purpose of teleoperation.

Figure 20 Simultaneous sequence of robotic and user fingers.

Figure 21 Showcasing several gestures
5 ACKNOWLEDGEMENT
This work is supported in part by U.S. National Science Foundation under Grant NO. 0525413 and CNS-0551598. The Author would like to thank Eli Worden of City College for design and fabrication of the robotic hand. Sincere gratitude also goes to Dr. Normal Scheinberg, Dr. Jizhong Xiao and Rex Wong for technical assistance and support.

6 REFERENCES


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