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The Magic Glove

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Abstract— **This article introduces an instrumented glove and its application for robotic and human-assisted material handling manipulators. In its simplest form, worn by an operator, the sensory glove measures the force the wearer imposes on any part of the material handling robot or the object being maneuvered by the material handling robot. This measured force is then transmitted as radio frequency (RF) signals to the controller of the material handling robot, which in turn maneuvers the load so that the human operator only needs to exert a small portion of the force, leaving the actuator of the system to provide the remaining force required. Therefore, the actuators of the material handling system add exertion only in response to the operator's hand force on the material handling system, or on the object maneuvered by the robot. Our experimental glove has proven entirely effective in manipulating objects naturally similar to the way we manipulate objects manually without activating many switches and pushbuttons to command the device.**

Index Terms—**Wireless, Glove, Robot, Assist Device**

I. INTRODUCTION

Compliance control for robotic systems has been utilized in industry during the last few years as intelligent assist devices. These intelligent assist devices are robotic systems wherein the human operator force on the device is measured and then amplified electronically to drive the device [4]. The sensory end-effector that measures the human operator force is physically connected to the material handling device. A signal, representing the human force imposed on the end-effector by the human operator is measured by the force sensor in the end-effector and transmitted to a controller which controls the actuators of the material handling device. The controller causes the robot to move the end-effector and load appropriately so that only a pre-programmed small portion of the load force is supported by the human operator and the remaining force is provided by the actuators of the robot. The robot responds only to the measured force from a force sensor in the end-effector. Thus, the robot is moved only by operator contact with the end-effector; it is not moved by operator contact with the object being maneuvered or any other part of the robot.

The objective of our research was to develop a general purpose module (i.e., an instrumented glove) that can be used with all kinds of robotic systems and convert them into intelligent assist devices. A robot that works with the instrumented glove described here does not need to have any force sensing end-effector, however, use of the instrumented glove described here will allow the operator to move the robot load by pushing onto any point on the load or onto any point on the robot itself. This instrumented glove is always worn by the operator and therefore remains with the operator. The instrumented glove generates a set of signals as a function of the contact force between the glove and the object being manipulated or the robot itself. A set of signals representing the contact force is transmitted in the form of RF signals to a robot controller so that a command signal is generated. The command signal is sent to the robot actuator to provide the required assistance to maneuver the robot as a function of the force imposed by the operator, so that the operator provides only a small portion of the total force needed to maneuver the robot and the object being manipulated by the robot. For a person observing the operator and the robot, this interaction seems rather magical since the robot responds to the operator’s touch regardless of whether the operator is pushing onto the robot or onto the object being lifted by the robot.

Fig. 1: A prototype instrumented glove is designed to measure the wearer contact force with a robot and broadcast a set of control signals representing the contact force for moving the robot.

Fig. 1 shows one of the prototype instrumented gloves that were designed in Berkeley. The instrumented glove essentially consists of two major components attached onto a fabric or leather glove: A *sensory system* to measure the operator force and a *transmission circuitry* to transmit the measured signals wirelessly. The sensory system is located in the palm of the operator’s hand to allow for measurement of the human operator force. The sensory system is designed to be compact; although it occupies very little space within the palm of the wearer, it still allows the wearer to grasp and manipulate small objects (e.g., hand tools) when he/she is not interacting with a robot. For convenience, the transmitter circuitry is located behind the glove.

Currently, instrumented gloves are used in various applications. For instance, gloves with actuators that create forces on the fingers according to a set of computer instructions are designed to emulate forces on the wearer's fingers and thumbs in telerobotics and virtual reality applications [1, 2, 3, and 5]. Another type of instrumented glove device includes sensors that measure kinematics type data (*i.e.*, position, orientation, and posture) of the fingers, thumbs and wrists for various applications[6, 7]. Applications for gloves with embedded sensors measuring kinematics type data include transforming human hand movements into electronic letters and characters controlling the movement and actions of video character, providing biofeedback for sports training such as tennis and golf, and assessing the mobility of human joints [8, 9].

We will first describe, through a simple example (also our experimental setup), how this instrumented glove can effectively be employed and what its limitations are. Then we will describe the architecture of the wireless data exchange that is employed in this system. A design section describing the details of the instrumented glove itself follows. Finally, once the characteristics of the wireless data exchange and the glove design are expressed, we will depict the dynamics and control of a system that is equipped with an instrumented glove.

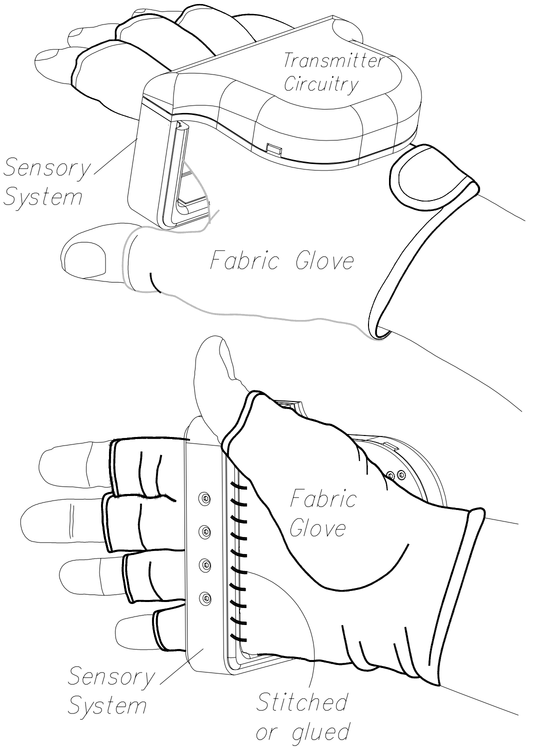

Fig. 2: An instrumented glove consists of two components: A *sensory system* to measure operator force and a *transmission circuitry* to transmit the measured signals wirelessly.

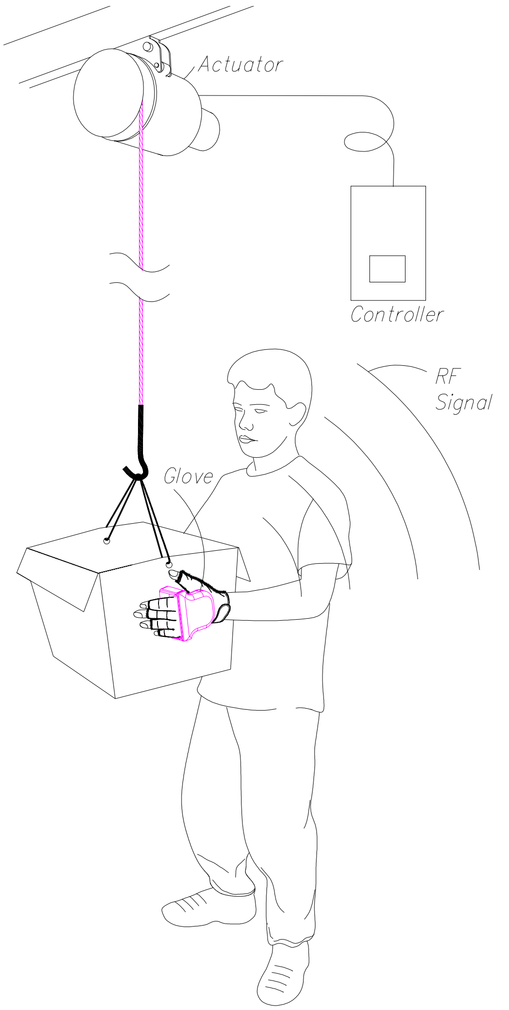

Fig. 3: An instrumented glove allows an operator to lift and lower objects naturally, while using a hoist, similar to the way we maneuver objects manually without activating switches or pushbuttons.

II. A SIMPLE EXAMPLE

Fig. 3 shows a simple example of how the instrumented glove can be used to control a one-degree-of-freedom assist device. At the top of the device, a take-up pulley, driven by an actuator, is directly attached to a ceiling or an overhead crane. Encircling the pulley is a wire rope. Attached to the wire rope is an end-effector. The end-effector shown in Fig, 3, consists of a hook only, although other types of grippers such as suction cups are also possible. The instrumented glove consists of a leather (or cloth) glove with an embedded sensory system (described in detail in later paragraphs). The embedded sensory system in the instrumented glove measures the force exerted by the human operator on the object being lifted (the container in Fig. 3) or on the lift assist device itself (e.g., the wire rope or the hook). The signal representing the operator vertical contact force is then sent to a transmitter circuitry on the back side of the glove. The transmitter circuitry transmits a set of control signals by means of radio frequency (RF) signals to a receiver circuitry installed in the controller of the lift assist device. Once the transmitted control signals are received, they will then be used for processing and control of the actuator of the lift assist device as a function of the measured operator vertical contact force. Using the data created by the receiver circuitry, the controller calculates the necessary actuator speed to either raise or lower the wire rope to create enough mechanical strength to assist the operator in the lifting task as required. If the operator pushes upwardly on the container, the take-up pulley moves the container upwardly. If the operator's hand pushes downwardly on the container, the take-up pulley moves the container downwardly. One of the important characteristics that the lift assist device now possesses is that the operator is able to lift and lower a load by contacting any point either on the load or on the lift assist device itself. The instrumented glove allows an operator to maneuver objects naturally; similar to the way he/she would maneuver objects manually without activating any switches or pushbuttons to command the device. Instead, the operator becomes an integral part of the device while maneuvering an object.

III. THE ARCHITECTURE OF THE WIRELESS DATA EXCHANGE

The term Radio Frequency (RF) refers to the electromagnetic field that is generated when an alternating current is input to an antenna. RF radiation has been used for wireless broadcasting and communications over a significant portion of the electromagnetic radiation spectrum -- from about 3 kHz to thousands of gigahertz (GHz). Many wireless devices make use of RF fields, for example, radio, television, cordless and cellular telephones, satellite communication systems, as well as many measuring and instrumentation systems used in manufacturing. RF signals have different frequencies, and by tuning a receiver to a specific frequency one can pick up a specific signal. In the U.S. the FCC (Federal Communications Commission) assigns a purpose to each frequency band. For example, all FM radio stations transmit in a band of frequencies between 88 megahertz and 108 megahertz. Similarly, AM radio stations are allowed to broadcast within a band from 535 kilohertz to 1,700 kilohertz. We used a 900 megahertz communication frequency which is also used in cordless phones.

Fig. 4 illustrates a schematic architecture of a wireless data exchange between the transmitter and the receiver circuitry. The transmitter circuitry is included in the glove while the receiver circuitry is inside the device controller. An essential part of the transmitter circuitry is the micro-controller. For the first generation of this project, we used an industry-standard, general purpose 8-bit micro-controller. There are a wide variety of micro-controllers and DSPs that are applicable to this design. The contact signals from the glove's sensory system are first read by the analog to digital converter (ADC) of the micro-controller and collected into the micro-controller's memory. The micro-controller subsequently generates a set of information signals as a function of the collected contact signals. This set of information signals is then passed to the RF transmitter module one bit at a time (serial streams) using the Serial Communications Interface (SCI) within the micro-controller. The data transfer rate of the transmitter module dictates the maximum rate at which our micro-controller can feed the RF transmitter module. The transmitter module used operates in the 902-928 MHz band and offers simplified integration into wireless product designs. Other features of the transmitter module include 8 selectable channels and the ability to transmit either analog or digital data. The transmitting antenna in the transmitter circuitry functions as a coupling device that allows for transmission of a set of RF waves as a function of the information signals collected by the transmitter module.

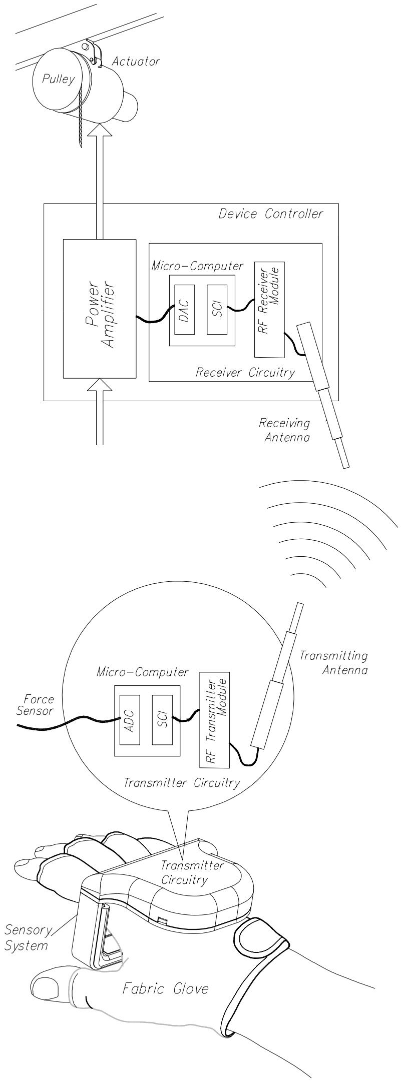

Figure 4: The wireless data transfer between the instrumented glove and the controller of the assist device.

The operator's vertical contact force is then transmitted as RF waves through the transmitting antenna, and can easily be collected by any receiving antenna. In our example, a flat antenna was used as the transmitting antenna due to its low profile. The compactness of this allows it to be concealed within the enclosure of the transmitter circuitry, which is better suited for portable devices. An alternative is a "whip" style antenna, which has a more cumbersome transmitter but would have afforded somewhat better performance. A battery with proper voltage is included in the transmitter circuitry to power all components of the glove. The structure and components of the receiver circuitry are in many ways similar to those of the transmitter circuitry. The receiver circuitry in our example is located inside the controller of the lift assist device. The controller contains three essential components: a receiver circuitry, a micro-computer, and a power amplifier. The receiver circuitry includes a RF receiver module and a receiving antenna. The receiver module receives RF waves through the receiving antenna**.** After detecting, filtering, and amplifying the transmitted signal, the receiver module presents the data to the micro-computer through a Serial Communications Interface (SCI). The receiver module operates in the same band as the transmitter module (902-928 MHz), which is separated into 8 selectable channels. The data received in the controller is used to control the speed of the actuator**.** A micro-computer with input/output capability and standard peripherals processes the data from the RF receiver module, sensors and switches and calculates the actuator speed necessary to create the required mechanical strength to assist the operator in the moving task. The micro-computer then generates command signals for the power amplifier through a Digital to Analog Converter (DAC) or Pulse Width Modulation channel (PWM). The power amplifier transfers power to the actuator.

IV. THE DESIGN OF THE INSTRUMENTED GLOVE

The instrumented glove essentially consists of two components: A *sensory system* to measure operator force and a *transmission circuitry* to transmit the measured signals wirelessly. Both the sensory system and the transmitter circuitry are stitched or glued to the glove. The transmission circuitry is mounted onto the sensory system, but located on the back of the operator's hand. Fig. 5 shows the sensory system and the transmitter circuitry (the glove is removed for clarity.) The sensory system, in our initial implementation, consists of two overlapping inner and outer brackets. The function of the inner bracket is to create a solid surface for the operator to push on. One important design feature of this inner bracket is its ability to slide freely relative to the outer bracket along the vertical direction. The sliding motion between the inner and outer brackets is very small and can be created by several methods. Fig. 6 shows an exploded view of the sensory system, where a Teflon-coated plate is employed between the inner and outer brackets, creating a smooth and frictionless motion in-between. Two force sensors (described in a later section) are installed on the outer side of the inner bracket. Note that the operator's hand, the glove and the inner bracket together are free to move relative to the outer bracket. Of course, this motion is very small (no more than a 0.1 mm). To illustrate the utility of this frictionless motion, suppose the operator's hand with the instrumented glove is in firm contact with a container (similar to that in Fig. 2) such that the surface of the outer bracket is touching the surface of the container. When the inner bracket (along with hand and glove) is pushed upwardly, the upper force sensor measures the upward compression force that the inner bracket imposes on the outer bracket. Similarly, when the inner bracket is pushed downwardly, the lower force sensor measures the downwardly compression force that the inner bracket exerts on the outer bracket. Since the outer bracket is in firm contact with a load, the forces measured by the sensors represent the forces imposed on the load by the outer bracket. Rubber strips are glued onto the force sensors to allow for concentration of the force on the force sensors. The base plate is connected to the outer bracket and prevents the outer bracket from sliding horizontally. The base plate adds structural rigidity to the system and creates a surface for installation of all components of the transmitter circuitry.

Fig. 7 shows another view of the integrated sensory system and the transmitter circuitry with the cover removed. A printed circuit board connected to the base bracket holds all the components of the transmitter circuitry, including the RF transmitter module, the micro-computer and the antenna. A 9-volt battery powers all components of the transmitter circuitry. The cover bracket can take on many forms and shapes; various non-metallic materials can also be used for its construction. The state of technology for mechanical design, material property and construction of the housing for the cordless telephone sets are directly applicable to the design of our cover bracket. The designers must make sure that the heat generated from the transmitter circuitry can be effectively removed through this bracket without letting dust or water in.

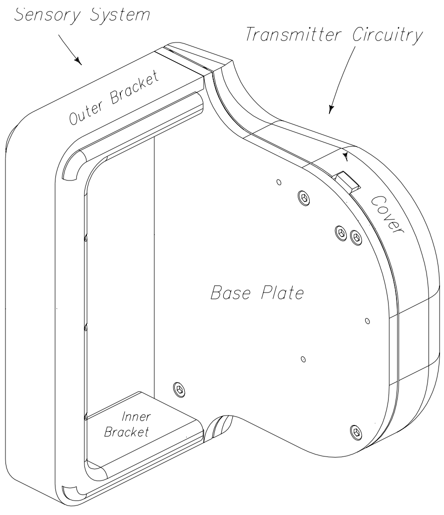

Fig. 5: Integrated sensory system and the transmitter circuitry.

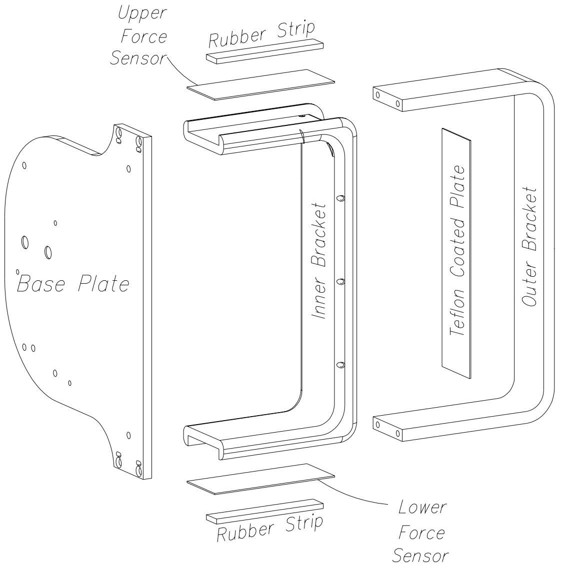

Fig. 6: An exploded view of the sensory system.

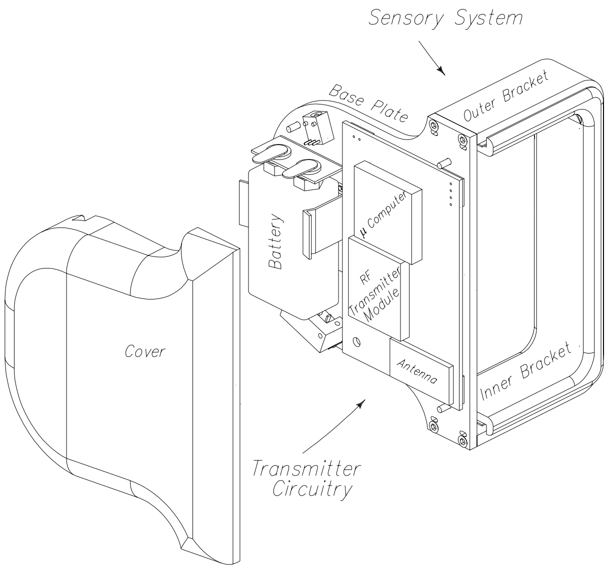

Fig. 7: The transmitter circuitry including the RF transmitter module, the micro-computer and the transmitting antenna.

V. FORCE SENSING

Many types of force sensors can be applied in the instrumented glove. However, one needs to choose small force sensors such that the operator's grasp and ability to manipulate small objects are not altered substantially. In our preliminary design, we used Force-Sensing Resistors (FSR) to measure the forces due to their low profile. As their name implies, FSR use the electrical property of resistance to measure the force (or pressure) applied to a sensor. The force-sensing resistor is a polymer thick film (PTF) device, which exhibits a decrease in resistance with any increase in force applied to the active surface. The resistive material serves to make an electrical path between the two sets of conductors.

For a typical FSR sensor, a human finger applying a force from 0.1N to 10N can cause the sensor to change resistance continuously from over 1MΩ to around 2KΩ. The FSR force vs. resistance characteristics are illustrated in Fig. 8 on a log/log format. At the low force end of the force-resistance characteristic, a switch-like response is evident. This threshold, or "break force", swings the resistance from greater than 1MΩ to about 50Ω -100Ω (the beginning of the power-law). At the high force end of the dynamic range, the response deviates from the power-law behavior, and eventually saturates at a point where increases in force yield little or no decrease in resistance.

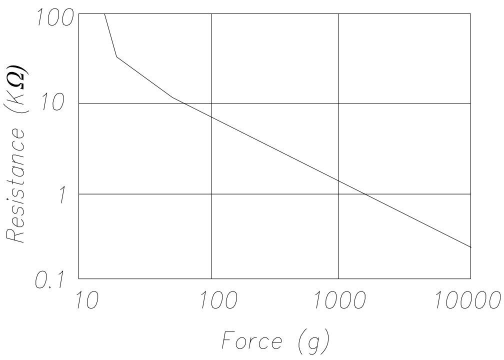

Fig. 8: Non-linear characteristics of FSR

Since FSR have non-linear characteristics, a conditioning circuit is designed to generate signals that represent the contact force properly to the micro-controller. Fig. 9 shows a conditioning circuitry needed to utilize a force-sensing resistor to generate a simple representation for the contact force. A 9-volt battery is used to provide power for the transmitter circuitry and the force-sensing resistor. A voltage regulator is used to generate a five-volt source (noted as V_C in Fig. 9). The capacitors are used to smooth the regulator output signal. Two 50KΩ resistors are used to create $V_C/2$. The use of operational amplifier and feedback resistor generates an output voltage V_o, such that:

$$V_O = \frac{V_C}{2}\left[1 - \frac{R_O}{R_{FSR}}\right] \tag{1}$$

where R_{FSR} and R_O are the resistances of the force sensing resistor and the feedback resistor, respectively. The output voltage, V_O, can then be read in the micro-computer of the transmitter circuitry. We chose a 1KΩ resistor for the feedback resistor. When no force is applied on the glove, R_{FSR} = 100KΩ, therefore, $V_O=V_C/2$. When the sensor is pressed down fully, R_{FSR} = 1KΩ and V_O=0. This means the output voltage, V_O, decreases when the force-sensing resistor is pressed. In this configuration, the range of the output voltage is from 0 to $V_C/2$.

While force sensing resistors were employed to measure the wearer force, other force measuring elements such as piezoelectric force sensing elements and strain gauge-based force detection devices can be used in the instrumented glove to measure the operator force. An important design issue here is the small size of the sensor. In some applications one might be interested in a sensory system with binary contact signals, which produces one output when the vertical contact force is zero and the inverse when the vertical contact force is present. The sensory system, in this case, can be instrumented by a series of momentary switches instead of a force sensor. When the operator pushes upwardly, a momentary switch is pressed and a set of contact signals will be sent to the transmitter circuitry representing a non-zero vertical upward contact force. When the operator is pushing downwardly against an object, another momentary switch is pressed and a different set of contact signals representing a non-zero vertical downward force will be sent to the transmitter circuitry. The systems constructed with momentary switches can be more economical to produce than ones with continuous force sensing capabilities. Alternatively, one can include arrays of force sensing elements on the glove to measure the wearer's forces along various directions.

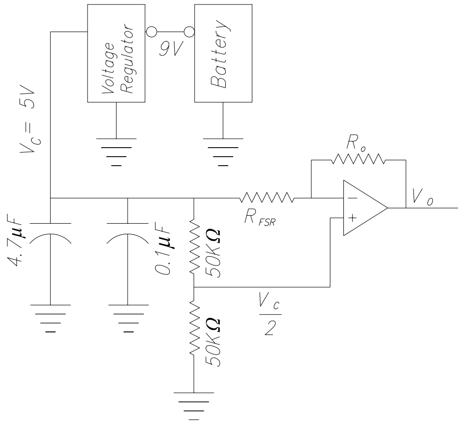

Fig. 9: A conditioning circuitry to utilize a FSR.

VI. CONTROL

The linear system theory is employed here to model the dynamic behavior of the elements in the system. This allows us to disclose the system properties in their simplest and most commonly used form. However, one can also use nonlinear models and follow the mathematical procedure detailed below to describe the system's dynamic behavior. The block diagram of Fig. 10 shows the basic control technique of a device that is equipped with the instrumented glove of Fig. 1. As discussed earlier, the force-sensing element in the instrumented glove delivers a signal to the controller, which is used to control the actuator. If (e) is the input command to the actuator, then the linear velocity of the end-effector v can be represented by:

$$v = G\,e + S\,f_R \tag{2}$$

where G is the actuator transfer function relating the input command to the actuator to the end-effector velocity; S is the actuator sensitivity transfer function relating the line tensile force f_R to the end-effector velocity, v. A positive value for v represents a downward speed for the load. Also note that since the load is connected to the end-effector, both terminologies "load velocity" and "end-effector velocity" refer to v as derived by equation 2. If a closed-loop velocity controller is designed for the actuator such that S is small, the actuator has only a small response to the line tensile force. A high-gain controller in the closed-loop velocity system results in a small S and consequently a small change in velocity v in response to the line tensile force. Also note that non-backdrivable speed reducers (usually high transmission ratios) produce a small S for the system.

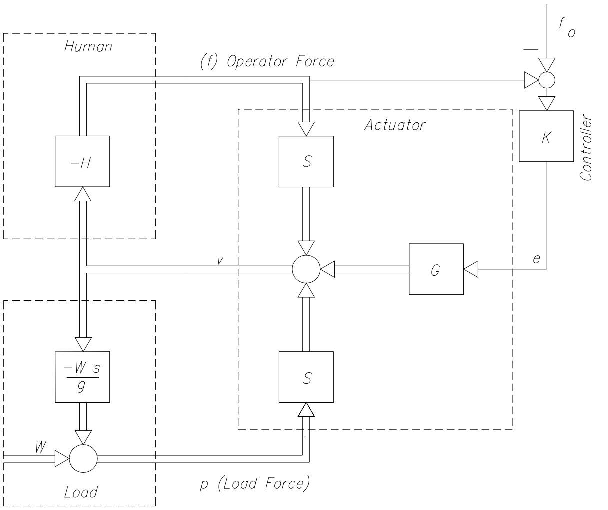

Fig. 10: The control block diagram

The rope tensile force, f_R, can be represented by:

$$f_R = f + p \tag{3}$$

where f is the operator-applied force on either the load, on the rope or on the end-effector; force p imposed by the load and the end-effector is referred to herein as the "load force" on the line. Positive values for f and p represent downward forces. Note that p is the force imposed on the line and is equal to the weight and inertia force of the load and end-effector taken together:

$$p = W - \frac{W}{g}\frac{d}{dt}v \tag{4}$$

where W is the weight of the end-effector and load taken together as a whole and $\frac{d}{dt}v$ is the acceleration of the end-effector and load. If the load does not have any acceleration or deceleration, then p is exactly equal to the weight of the end-effector and load W. The operator force f is measured and passed to the controller delivering the output signal e. A positive number f_o in the computer is subtracted from the measurement of the human force f. The role of f_o is explained below. If the transfer function of the controller is represented by K, then the output of the controller e is:

$$e = K(f - f_o) \tag{5}$$

Substituting for f_R and e from equations (3) and (5) into equation (2) results in the following equation for the end-effector velocity v:

$$v = GK(f - f_o) + S(f + p) \tag{6}$$

Measuring an upward human force on the end-effector or on the load is only possible when the line is under tension from the weight of the end-effector. If the end-effector is light, then the full range of human upward forces may be neglected by the sensor in the instrumented glove. To overcome this problem, a positive number, f_o, is introduced in equation (5). As equation (6) shows, the absence of f and p will cause the end-effector to move upwardly. Suppose the maximum downward force imposed by the operator is f_{max}. Then f_o is preferably set at approximately half of f_{max}. Substituting for f_o in equation (6), equation (7) represents the load velocity:

$$v = GK\,(f - \frac{f_{max}}{2}) + S\,(f + P) \tag{7}$$

If the operator pushes downwardly, such that $f = f_{max}$, then the maximum downward velocity of the load is:

$$v_{Down} = GK\,(\frac{f_{max}}{2}) + S\,(f + P) \tag{8}$$

If the operator does not push at all, then the maximum upward velocity of the end-effector or the load is:

$$v = -GK\,(\frac{f_{max}}{2}) + S\,(f + P) \tag{9}$$

Therefore, by the introduction of f_o in equation (5), one need not be concerned about the measurement of the upward human force. If S=0, the upward and downward maximum speeds are identical in magnitude. However, in the presence of non-zero S, for a given load and under equal conditions, the magnitude of the maximum upward speed is smaller than the magnitude of the maximum downward speed. This is very natural and intuitive for the operator. Going back to equation (6), it can be observed that the more force an operator imposes on the load or on the line, the larger the velocity of the load and end-effector will be. Using the measurement of the operator force, the controller assigns the proper pulley speed to create sufficient mechanical strength, in order to assist the operator in the lifting task. This way, the end-effector follows the human arm motions naturally.

Equation (6) suggests that, when the operator increases or decreases the downward force on an object, a corresponding increase or decrease occurs in the downward speed of the object. Alternatively, an increase or decrease in the object's weight causes a decrease or increase, respectively, in the upward object speed for a given operator force on the object. As Fig. 10 indicates, K may not be arbitrarily large. Rather, the choice of K must guarantee the closed-loop stability of the system. The human force f is a function of human arm impedance H, whereas the load force is a function of load dynamics, i.e., the weight and inertial forces generated by the load. One can find many methods to design the controller transfer function K. Reference [4] describes the conditions for the closed-loop stability of the system.

VII. CONCLUSION

This paper describes a sensory glove is which worn by an operator and measures the vertical force that the wearer is imposing on an object that is being maneuvered by the lift assist device or on the lift assist device itself. The measured force is then transmitted in terms of radio frequency (RF) signals to the controller of the lift assist device. The lift assist device lowers and lifts the load so always the human operator exerts a pre-programmed small portion of the force, and the actuator of the material handling device provides the remaining force. Several sensory gloves were designed and built to verify the system effectiveness.

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