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SERVOMOTOR-LINKED ARTICULATED VERSATILE END EFFECTOR (SLAVE^2)

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ABSTRACT

A strategy is presented for the design and construction of a large master/slave-controlled, five-finger robotic hand. Each of the five fingers will possess four independent axes each driven by a brushless DC servomotor and, thus, four degrees-of-freedom. It is proposed that commercially available components be utilized as much as possible to fabricate a working laboratory model of the device with an anticipated overall length of approximately three feet (0.9 m). The fingers are to be designed to accommodate proximity, tactile, or force/torque sensors imbedded in their structure. In order to provide for the simultaneous control of the twenty independent hand joints, a multilevel master/slave control strategy is proposed in which the operator wears a specially instrumented glove which produces control signals corresponding to the finger configurations and which is capable of conveying sensor feedback signals to the operator. Two dexterous hand master devices are currently commercially available for this application with both undergoing continuing development. A third approach to be investigated for the master control mode is the use of real-time image processing of a specially patterned master glove to provide the respective control signals for positioning the multiple finger joints.

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Design Objectives

Development is underway to design and construct a large, five-finger, anthropomorphic, master/slave-controlled, robotic hand. The envisioned device would be larger and more powerful than the human hand while possessing sufficient dexterity to closely mimic the fingering and grasping configurations of its human counterpart. Control signals would be generated by a master glove worn by the operator. The device has been assigned the acronym, $SLAVE^2$ for, "Servomotor-Linked Articulated Versatile End Effector," reflecting the planned master/slave control mode and the use of an individual electric servomotor to drive each joint.

Anticipated commercial applications include handling of hazardous wastes, munitions, or large radioactive or chemically contaminated objects. Fire fighting, construction, demolition, disaster clean-up, and rescue operations might provide additional applications for a large, dexterous end effector operated remotely under master/slave control.

A rapid prototype R&D strategy utilizing off-the-shelf components wherever possible is being employed for the development of the $SLAVE^2$ laboratory prototype. A key goal of the strategy is to minimize development time and costs by eliminating long lead times for design and construction of individual components. Thus, commercial availability of components, including the electric servomotors and power transmission mechanisms to drive the individual finger joints, will dictate size, weight, payload and finger length of the hand assembly. Based upon this consideration and current design estimates, it is anticipated that the initial working laboratory model will be approximately four-times human size with an overall hand length of approximately three feet (0.9 m) and an individual fingertip clamping force of 10-12 pounds (44 - 53 N). It is expected that the finger will have a typical length of about 18 inches (46 cm) and weigh approximately 15 pounds (6.8 kg). Initial estimates indicate that a frequency response of 0.5 Hz can be achieved.

Proposed Robotic Hand Design

Mechanical Configuration

A mechanical hand configuration possessing four fingers and a thumb is contemplated. Each of these five members will have four joints or degrees-of-freedom. More specifically, for each finger/thumb member three joints would provide flexion and extension (and possibly hyperextension) and a fourth joint would allow abduction and adduction. This would give the hand a total of twenty degrees of freedom and provide sufficient dexterity to closely replicate the gripping and fingering actions of a human hand.

The goal of the first year of the development effort currently underway is to develop a working laboratory prototype of a single four degree-of-freedom finger. Initial emphasis has been placed upon the selection of the most desirable mechanical configuration for the compound knuckle joint which must provide for both flexion/extension and abduction/adduction angular motions. In arriving at a prototype design a number of different mechanical configurations were considered before selecting the arrangement shown in the sketch of Figure 1. This configuration features coincident flexion/extension and ab/adduction axes and provides for the drive motors for these two axes to be mounted on the stationary palm rather than on the moving finger.

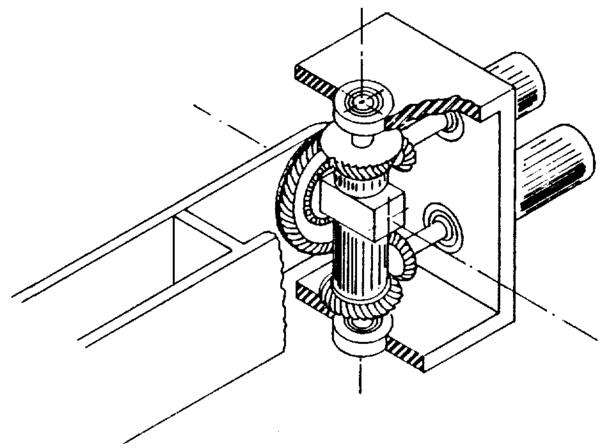

Figure 1 - Compound Axis Knuckle Joint Configuration

Drive Component Selection

The selection of the drive components to power the finger joints was governed by a desire to achieve optimum performance and compactness while utilizing commercially available components to the greatest extent possible. Thus, an attempt was made to balance the load capacity of the servomotors, gear reducers, and right angle drive units. In this regard, when evaluated on the basis of torque capacity-to-density (weight and compactness), the right angle drive units surprisingly proved to be the limiting factor in achieving greater payloads.

Servomotors

Each of the twenty joints is to be directly driven by an independent brushless DC servomotor and integrated speed reducing mechanism. Although practical brushless DC servomotors are a relatively recent development triggered by advances in solid state electronics and permanent magnet technology, units are now available from a number of major manufacturers. The selection of 24 volt DC brushless motors from the Inland Motor Division of Kollmorgen Corporation was based upon high torque-to-density ratios and the convenient operating voltage range. The brushless DC type of servomotor duplicates the external performance of a conventional DC motor without utilizing a commutator or brushes. This is possible because solid-state electronic switching replaces the conventional brush commutation switching process. A second major difference is that the wound member, or armature, reverses its role and relative position from rotor (rotating member) and inner component in the conventional DC motor, to stator (stationary member) and outer component in the brushless motor.

These two differences lead to a number of significant advantages from the brushless DC motor with respect to performance, safety and reliability [1,2]:

1. No brushes to wear out: increased reliability, reduced maintenance requirements.
2. No commutator bars to oxidize: ability to sit idle for years without loss of performance.
3. Absence of brush arcing: safer in the presence of fumes, dust, paint spray, etc.
4. Speeds up to 80,000 RPM are practical.
5. Less radio-frequency interference.
6. Easier cooling of windings with fins or cooling jacket: extended operating range.
7. Smaller diameter, more compact.
8. Reduced inertia: increased acceleration and improved control.

Power Transmission

Electric motors characteristically produce relatively low torque in the low speeds range. This is true as well for brushless DC motors, and preliminary calculations indicate that torque multiplication (or speed reduction) rates of about 100:1 will be required to achieve the desired robotic hand strength. To meet this requirement, the patented harmonic drive gearing device available from the Harmonic Drive Division of the Emhart Machinery Group, Wakefield, MA, has been identified.

The unique design of the harmonic drive with three simple concentric components yields the following advantages for robotics gear reduction applications:

1. Exceptionally high torque and power capability in a small package.
2. Essentially zero backlash.
3. Efficiencies as high as 90%.
4. Ratios as high as 320:1 in a single reduction with much higher ratios achieved by compound stages.
5. Concentric input and output shafts.
6. No radial loads since torque is generated by a pure couple; this simplifies the supporting structure requirements.
7. Resists back driving, providing a measure of braking.

Drawbacks of the harmonic drive are that it is relatively compliant exhibiting a soft windup characteristic in the low torque region, and that it produces a small, sinusoidal positional error on the output. This error varies inversely with the pitch diameter at a predominant frequency of twice the input speed. Additionally, an amplitude modulation typically occurs twice per output revolution.

A detailed explanation of the operating principles is given in the "Harmonic Drive Designers Handbook" [3] along with load and accuracy ratings, operating life expectancies and installation and servicing guidelines.

In view of the need to maintain a slender aspect ratio in the design of the finger configuration, it is necessary to utilize a right angle drive mechanism to provide torque about an axis perpendicular to the axis of the servomotor-harmonic drive assembly. For this purpose spiral bevel gears manufactured by the Arrow Gear Company of Downers Grove, Illinois, were selected. This type of gearing features efficient and smooth operation and relatively high strength.

Electronic Programmable Controllers

With the many degrees of freedom required for dexterous robot hands, the problem of control and demand on computing escalates. The simplest approach is to use a local control loop for each joint. However, for precise motion control, a coordinated motion for all joints is essential for an efficient design.

For master-slave operation, where the coordination is achieved by the action of a human in the loop, the coupling between the fingers is neglected. Currently, a number of high performance servomotor controllers are commercially available. These controllers are designed to be programmable and installed in personal computers.

The Galil DMC/600 series Advanced Motion Controller has been selected to fulfill this role in the finger prototype development. The DMC/600 is a fully programmable servo motion controller contained on an IBM PC compatible card. It controls the motion of up to three DC motors with incremental encoder feedback. Modes of motion include independent or vector positioning, contouring, jogging and homing. A FIFO buffer allows fast pipelining of instructions. The DMC/600 contains a digital filter with an integral gain term for eliminating position error at stop. Several error handling features are available including automatic shut-off for excessive position error, limit switch inputs, emergency stop inputs and programmable torque limits.

Dexterous Hand Masters

The proposed master/slave control mode calls for the operator to wear a specially instrumented dexterous hand master. This device must produce control signals capable of directing the servomotor actuators of the robotic slave hand into correspondence with the respective positions of the human operator's hand joints. Plans call for consideration of three different dexterous hand masters to carry out this control function. Two such devices, the A. D. Little "Sarcos Dexterous Hand Master" and the VPL Research "DataGlove" are currently commercially available though both are undergoing continuing development. Their application will be discussed briefly in the following paragraphs together with a third approach utilizing real-time image processing of a special optically patterned master glove.

Arthur D. Little, Inc. of Cambridge, Massachusetts [4,12] offers a Sarcos Dexterous Hand Master. The device utilizes mechanical linkage assemblies secured to the individual finger digits by means of flexible ring-like bands. Built-in hall effect potentiometers translate the various linkage motions into electrical signals which can be correlated to the individual finger joint movements.

VPL Research of Redwood City, California markets the DataGlove [5-7], an ingenious glove-like dexterous hand master that senses hand gesture position and orientation in real time. The device utilizes fiber-optic cables sandwiched between a stretchable inner glove and a cloth outer glove. Each joint motion to be detected requires a separate fiber-optic cable laid in a parallel path running across the joint and looping back so that both free ends are anchored in an interface board mounted near the wrist. At one end of the cable is a light emitting diode source and at the other a phototransistor. The segments of the cable which rest over the joint are specially treated so that the light escapes when the joint is flexed. The greater the degree of bending, the greater is the loss of transmitted light. This effect can be detected by the phototransistor and calibrated to provide angular measurements with a resolution of one degree. A data acquisition rate of 60 times per second is used.

A third method suggested for the master control mode is the use of a master glove imprinted with a special color-coded optical pattern. In this approach, the respective control signals for positioning the multiple finger joints would be extracted from the glove image. Potentially, the patterned glove could be lighter, better fitting, less cumbersome, and less expensive than either the A. D. Little Sarcos Dexterous Hand Master or VPL DataGlove. The authors are not aware of any commercially available devices of this nature or any researchers who have applied this approach to date.

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