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An Anthropomorphic Hand Exoskeleton to Prevent Astronaut Hand Fatigue During Extravehicular Activities

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Steven W. Peterson, and Alvin M. Strauss

***Abstract*—This correspondence presents a prototype of a powered hand exoskeleton that is designed to fit over the gloved hand of an astronaut and offset the stiffness of the pressurized space suit. This will keep the productive time spent in extravehicular activity from being constrained by hand fatigue. The exoskeleton has a three-finger design, the third and fourth fingers being combined to lighten and simplify the assembly. The motions of the hand are monitored by an array of pressure sensors mounted between the exoskeleton and the hand. Controller commands are determined by a state-of-the-art programmable microcontroller using pressure sensor input. These commands are applied to a PWM driven dc motor array which provides the motive power to move the exoskeleton fingers. The resultant motion of the exoskeleton allows the astronaut to perform both precision grasping tasks with the thumb and forefinger, as well as a power grasp with the entire hand.**

***Index Terms*—Glove, hand fatigue, mechanical hands, space suit, telerobotics.**

I. Introduction

One area where exoskeleton development could prove useful is in assisting astronauts in performing extravehicular activities (EVA). The current NASA EVA gloves must perform a number of critical protection and isolation functions while remaining flexible enough so that astronauts can do useful work. To date safety and durability considerations have understandably been given the most attention. One unfortunate side effect of this focus are space suit gloves with less than desirable flexibility.

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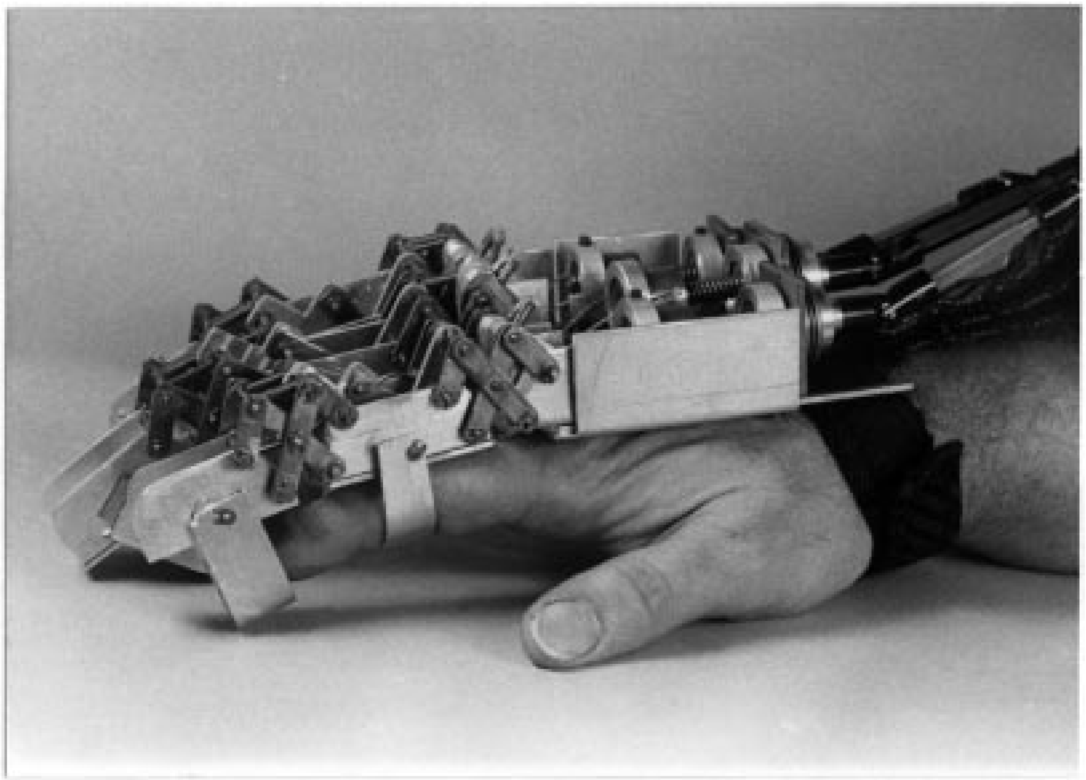

Fig. 1. Photograph of the exoskeleton in its extended position.

Space suits and gloves are essentially balloons, and like balloons they have a characteristic neutral shape. Any change from this neutral shape requires mechanical work both to displace the glove and to hold in a given position. Because of this stiffness the EVA glove has been noted as one of the limiting factors in EVA productivity [1]. The metacarpophalangeal joint is particularly problematic because its flat geometry causes the glove to balloon around it resulting in a larger, and therefore stiffer, glove than necessary. The purpose of this effort was to develop a hand exoskeleton system to assist astronauts in performing tasks in which glove stiffness would normally fatigue their hands.

While the problem of suit stiffness has been around since the early days of space suit development, the application of exoskeleton technology directly to this issue is relatively new and limited. A rare example of a space suit exoskeleton application is a proposed EVA suit motorized wrist joint [2]. Much more information is available in the literature on general exoskeleton design for a variety of applications. Information and design ideas were liberally borrowed from previous studies in this development effort [3]–[6]. The goal of these previous exoskeleton designs was to assist the human operator in overcoming physical limitations. This present work has an similar goal. By augmenting the strength of the human hand the exoskeleton provides a unique way of assisting astronauts in overcoming the stiffness of the EVA glove.

II. General Design Criteria

It is difficult, perhaps impossible, to predict the motions that a suited astronaut will be required to make with his or her hands during EVA. Designing a hand exoskeleton, however, requires some decisions about what kind of motions are necessary. To avoid the difficulty in defining specific hand motions the requirements are kept as general and therefore as flexible as possible for the space suit glove exoskeleton: the only specifications set down at the beginning of the design process were that the exoskeleton should have the capability to perform both a power hand grasp and a precision finger grasp [7]. A power grasp is one in which there are large areas of contact between the fingers and the palm, with little ability to impart motion to the fingers. This type of grasp is performed when security and stability are primary concerns. An example is grasping the handle of a tool or a handrail. A precision grasp involves a pinching motion between a finger and the thumb. This type of grasp is performed when dexterity and sensitivity are desired.

The second design goal was that the kinematics of the exoskeleton follow that of the human hand as closely as possible. A critical fact that must be accounted for in the development of a hand exoskeleton is that the phalanges of the finger rotate about a point located inside their respective joints. For the exoskeleton joints to mimic the motion of the fingers their centers of rotation should coincide with the centers of rotation of the actual fingers. This task of following human motions with an exoskeleton is extremely difficult since human movement systems are complex with many degrees of freedom. A mechanism that synthesizes a human-type motion will necessarily also be complex, particularly from the control standpoint. Therefore, researchers in this area have often tried to reduce the number of degrees of freedom to as great an extent as is practical [8]–[9].

III. Exoskeleton Kinematics

To meet the specifications laid down in the previous sections a three-fingered exoskeleton prototype was designed and constructed. Figs. 1–3 are photos of the finished product. The three-fingered design allows independent movement of the index finger and middle finger, and combines the ring and little finger. Each exoskeleton finger mimics the movement of the wearers' metacarpophalangeal (MCP)

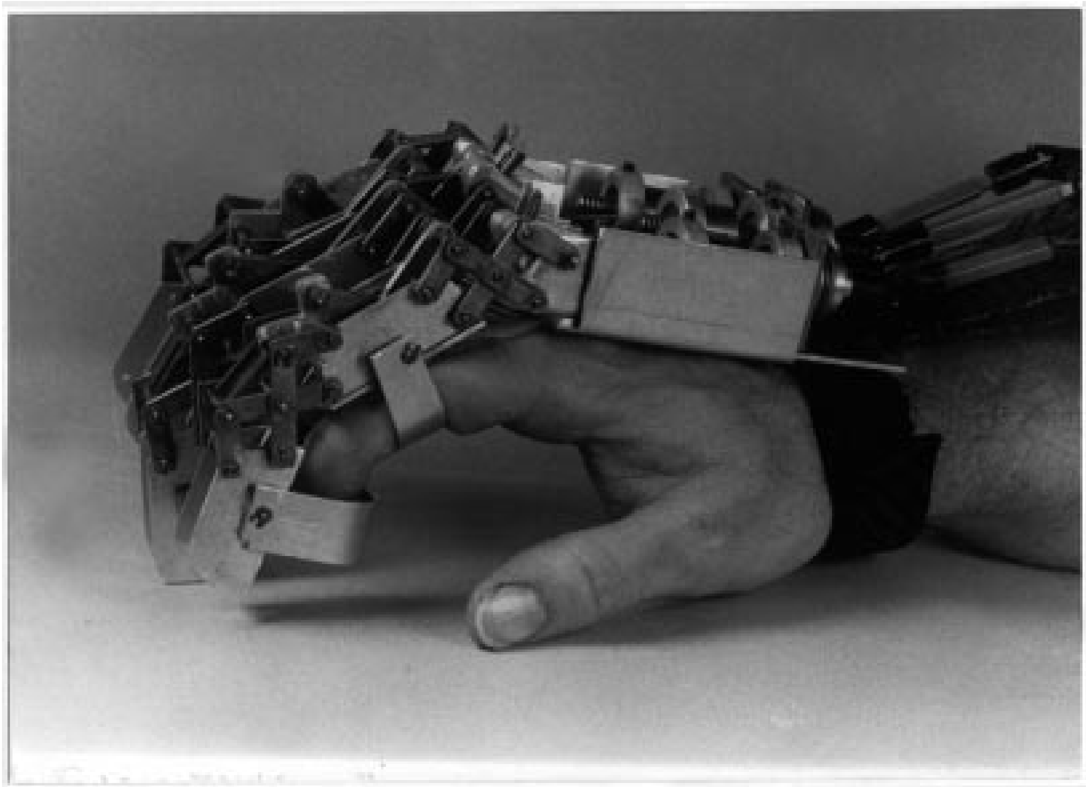

Fig. 2. Photograph of the exoskeleton in its closed position.

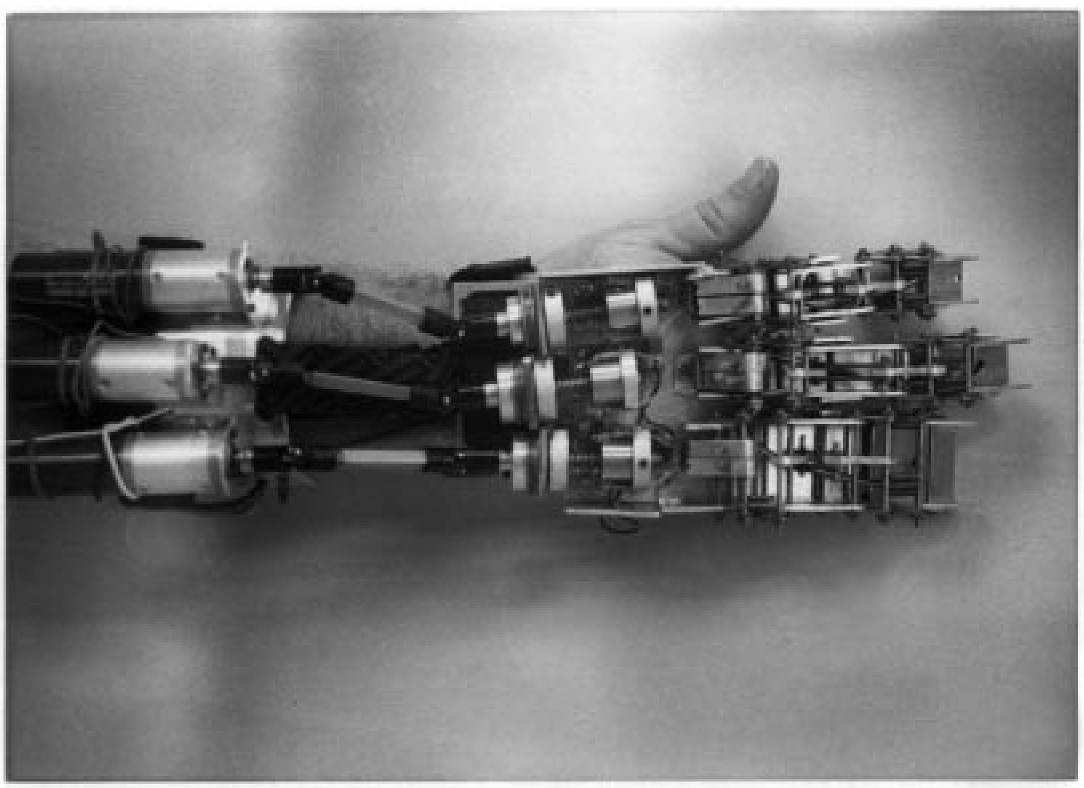

Fig. 3. Top view of exoskeleton prototype.

and proximal interphalangeal (PIP) joint. A separate drive and sensor system is used for each finger so that they may operate independently. The fingers are enclosed in the exoskeleton by semicircular brackets that are mounted on the exoskeleton fingers. These brackets protect the fingers from physical harm and provide a convenient location for sensor placement.

Using standard methods of linkage synthesis, the exoskeleton finger joint mechanism shown in Fig. 4 was designed to mimic human finger

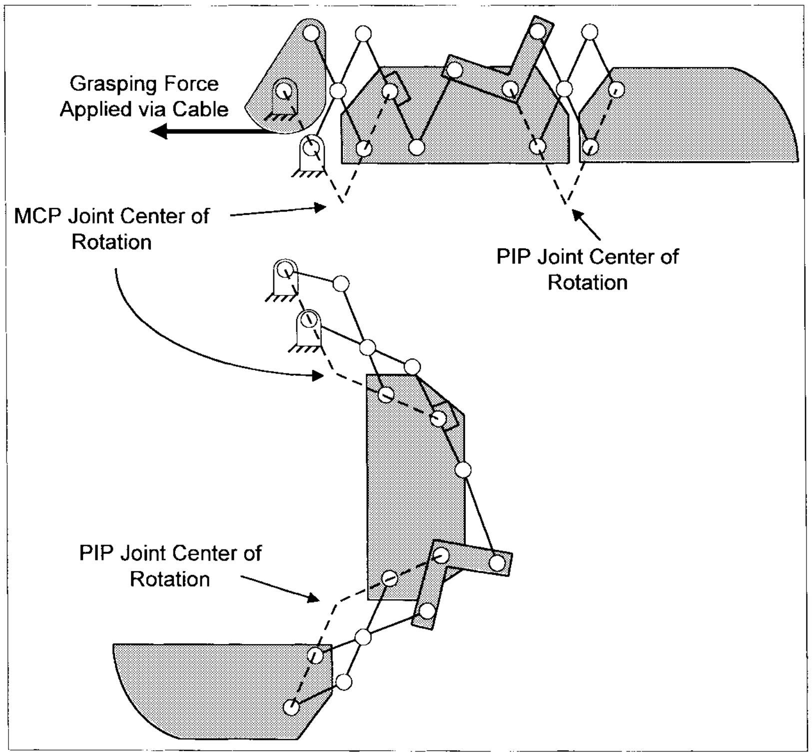

Fig. 4. Sketch of the design and kinematics of the exoskeleton fingers.

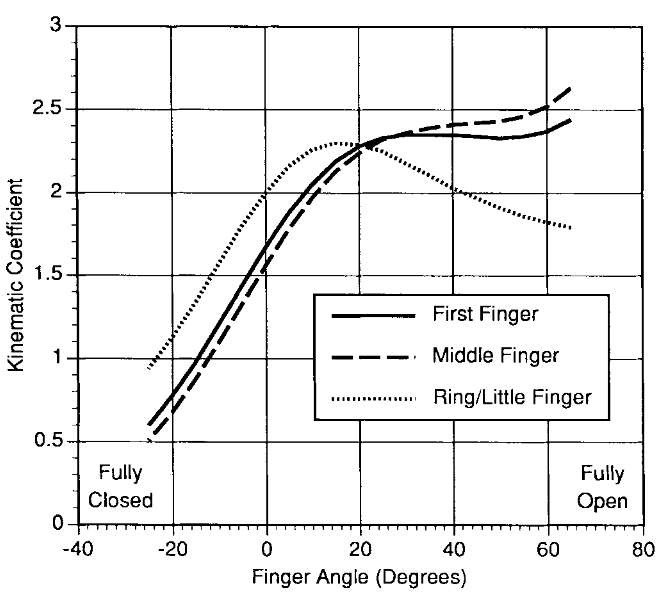

Fig. 5. Plot of the kinematic coefficients relating the rotation of the distal phalange to the input link.

kinematics. Each joint uses a four-bar mechanism to rotate about an instant center that corresponds to the instant center of the proximal phalanx with respect to ground and the middle phalanx with respect to the proximal phalanx. These locations are shown in Fig. 4 in the open and closed positions, respectively. Because of the parallelogram structure of the mechanism the instant centers remain fixed relative to the ground link in each joint. The design of each joint mechanism was governed by having the appropriate instant centers coincide with the centers of rotation of the wearers' fingers. This was the guiding factor in determining the length of each link and the initial angles between the links. This also means that an exoskeleton is a custom-made device due to the large amount of human variation in hand size.

The kinematic coefficient relating the proximal exoskeleton link to the input link has a constant value of 1 for all three exoskeleton fingers. In order to reduce the number of degrees of freedom of the hand exoskeleton the actions of the distal exoskeleton phalanges were coupled to the proximal links through an additional four-bar transmission mechanism mounted on the proximal phalange as shown in Fig. 4. The resulting kinematic coefficients that relate the motion of the proximal phalanges to the input links are plotted in Fig. 5.

Torque is applied to the input link of each finger by a cable driven cam system, also shown in Fig. 4. The cam is designed so that the moment arm associated with the cable tension has a constant value of 1 cm over the range of motion of the exoskeleton fingers. The remainder of the drive system is best illustrated in Fig. 3. The cable wraps under the input link cam and connects to a lead screw nut. The lead screw is mounted to the exoskeleton backplane with a collar bearing. This allows the lead screw to be driven via a telescoping universal joint by an array of permanent magnet dc motors with integrated gearheads that are mounted on an independent forearm plate. Note that this actuation system is capable only of closing the exoskeleton hand due to the ability of the cable to only carry tensile loads. The stiffness of the space suit glove itself will provide the force to open the exoskeleton.

This transmission system is capable of providing a torque to the finger input link of approximately 3.8 Nm. Research has indicated that the necessary torque to bend the metacarpophalangeal joint of a space suit glove 90° is in the 1–2 Nm range [10].

IV. Control System/Sensors

The input to the control system was chosen to be the pressure exerted by the wearer on the distal semicircular protection bracket of

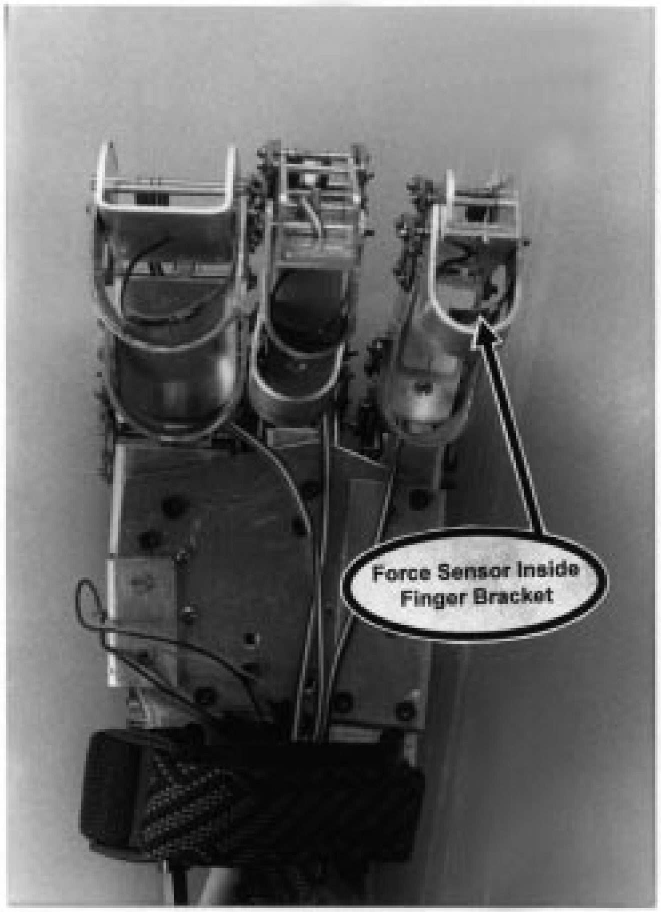

Fig. 6. Detail of the hand/exoskeleton contact pressure sensors.

Fig. 7. Palmar view of the exoskeleton.

each finger. The sensor developed to gather this information is shown in Fig. 6. It consists of a strip of brass gage stock that is bent into a "J" shape and fits inside the distal finger bracket of each exoskeleton finger. Mounted on the gage stock is a temperature-compensated strain gage. The amplified and filtered output of the strain gage bridge provides a monotonic, calibratable signal that reflects the force of wearer's hand pressing against the finger bracket. Since the motion of the proximal and distal links of the exoskeleton fingers are coupled, only one force sensor per finger is necessary. Therefore only the brackets attached to the distal exoskeleton link contain force sensors. Fig. 7 shows the palm of the hand and the contact between the fingers and the force sensors.

A digital control system was breadboarded to translate the sensor output into motor commands. The system incorporates a programmable logic controller (PLC) based on the Intel 83C51FB microprocessor. Digital control allows more flexibility than an analog control system since different control schemes can be invoked by simply modifying the software. The microcontroller used in the prototype also has on-board analog-to-digital conversion and is very compact.

The microcontroller was programmed using assembly language to maximize performance and allow the use of interrupt routines. The particular control scheme used in the prototype development effort is a simple threshold scheme that causes the output of a pulse-width-modulated control wave for the dc motor driving circuit. Two pressure threshold levels set in software are necessary with this method. If the input voltage level from a finger sensor is lower than a certain threshold voltage, the PWM output wave is positive, causing the motor to open the appropriate finger. If the voltage corresponding to the contact force increases above the bottom threshold, the output to the motor is stopped, causing the motor to stop turning and the lead screw to lock. As the contact force increases further the second threshold is crossed and the PWM wave that is output is negative, causing the finger to close in response to the increased finger pressure. This control scheme by no means represents the most sophisticated method possible with this controller, but was sufficient for mechanical testing and some simple prototype evaluation.

The microcontroller-based analog-to-digital converter is used to digitize the signal from the finger contact sensors. Noise filtering is accomplished by storing 16 consecutive samples and calculating the average. This average is then compared to the set threshold values and the appropriate action determined by the microcontroller. The interrupt routine is capable of sampling all three sensors and producing averaged values every 29 ms.

The 5 V peak PWM wave output from the microcontroller is amplified by a dual power op-amp (APEX PA26). These amplifiers were chosen because they are well suited for bidirectional speed control from a single supply, allowing the motors to run from full-scale clockwise to full-scale counterclockwise.

V. Prototype Evaluation

A series of simple tests were conducted in order to evaluate exoskeleton capabilities and the design decisions made with regard to the prototype. The test subject, for whom the hand exoskeleton had been specifically designed, reported that it fit on the hand with little discomfort. Simple tests of the power grasp motion demonstrated that the device successfully mimicked the kinematics of the hand joints. The simple threshold control system also functioned surprisingly well in both opening and closing the exoskeleton. Unloaded the exoskeleton moved from the fully open position to fully closed position in 2 s.

These simple hand motion tests also brought to light the only significant problem with the prototype, however. The root of the problem was the reduction of the many degrees of freedom of the hand to one per finger in the prototype. The human hand has over 25 degrees of freedom, many of which are coupled by the ligamentous structure and location of tendon insertions [11]. This coupling was clearly evident during exoskeleton tests. If motion of a single finger was attempted, the other fingers also moved to a certain extent. At times these hand motions were detected by the sensor array, causing undesired exoskeleton motion. One obvious solution to this problem is to add more degrees of freedom to the exoskeleton. This will unfortunately also result in added complexity, weight, and bulk, not to mention a more sophisticated controller.

Simple tests were also performed to evaluate the ability of the exoskeleton to perform the precision grasp with the thumb and forefinger. These precision tasks proved much easier than the power grasp motion. This does not appear to be due to any unique characteristic of the hardware or software, but is a natural result of the sensory feedback provided the operator by the human thumb, which is neither powered nor enclosed in this exoskeleton. A true exoskeleton thumb would be needed to overcome the thumb stiffness in the real glove, so little insight can be gained from these tests with respect to the precision grasp capabilities other than it would clearly require a more sophisticated control system than the simple threshold scheme used here. In such an application the control system would have to be programmed to only supply enough force to overcome the glove stiffness in order to give the astronaut a bare-handed illusion.

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Model-Based Fault Diagnosis Using Fuzzy Matching

A. L. Dexter and M. Benouarets

***Abstract*— A new fuzzy-model-based approach to fault detection and diagnosis is proposed. The scheme uses a set of fuzzy reference models which describe faulty and fault-free operation, and a classifier based on fuzzy matching for fault diagnosis. The reference models are obtained off-line from simulation data. A fuzzy model which describes the actual behavior of the plant is identified on-line from normal operating data and compared to each of the reference models. A degree of similarity is evaluated every time the on-line fuzzy model is identified. Dempster's rule of combination is used to combine new evidence with that already collected. The method of diagnosis accounts for any ambiguity (which may result from fault-free and faulty operation, or different faults, having similar symptoms at a given operating point) by comparing the fuzzy reference models with each other. Results are presented which demonstrate the effectiveness of the scheme when it is used to detect and identify faults in the cooling coil subsystem of the air-handling unit of both simulated and experimental air-conditioning plant.**

I. Introduction

System operation is subject to many factors such as degradation of plant performance caused by wear, failures resulting from physical defects in equipment, or inappropriate tuning of the control system. By monitoring the operation, fault detection and diagnosis (FDD) schemes can detect and identify any malfunctions, thus improving performance, enhancing safety and reducing maintenance costs. Many of these FDD schemes are model-based and have two common components: a preprocessor and a classifier. The preprocessor generates error signals (usually called residuals) either by comparing measurements taken from the actual system to those predicted by one or more reference models [1], or by comparing the parameters of the reference models to values of the parameters estimated on-line from the measurements [2]. The classifier relates the error signals to normal or faulty operation.

Most of the existing model-based schemes use quantitative models to estimate the states or parameters of the system and to generate the error signals. However, a major problem associated with this approach is that in practice it is almost impossible to obtain a model that exactly matches the process behavior [3]. The mismatch between the behavior of the model and the plant may lead to large error signals which can cause false alarms unless appropriate thresholds are used [4]. However, the selection of appropriate thresholds may be problematic in nonlinear systems, since the accuracy of the model will depend on the operating conditions, and the thresholds must be varied so as to adapt to changes in the operating point [5]. In practice,

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