# Design of Orientation-Free Handler and Fuzzy Controller for Wire-Driven Heavy Object Lifting System

Bo-Wei Song, Yun-Jung Lee

***Abstract***—This paper presents an intention interface and controller for a wire-driven heavy object lifting system that assists the operator with moving a heavy object. The handler is designed to allow a comfortable working posture for the operator. Plus, as a human assistive system, the operator is involved in the control loop, where a fuzzy control system is used to consider the human control characteristics. The effectiveness and performance of the proposed system are proved by experiments.

***Keywords***—Fuzzy controller, Handler design, Heavy object lifting system, Human-assistive device, Human-in-the-loop system.

## I. INTRODUCTION

THE operation of lifting heavy objects is used in many different situations, such as moving suitcases from airport conveyer belts, loading packages at mail service centers, patient transportation in the medical field, and loading agricultural products. In these situations, the main characteristics of the lifting operations include variable weights and sizes of the lifted objects and a moving working location, making it difficult to use completely automated systems instead of human workers.

Thus, a lot of research has been focused on developing Intelligent Assistive Devices (IADs) that can help human workers to lift heavy objects using minimal force, thereby avoiding physical exhaustion and possible injury. Some example IADs are shown in Fig. 1.
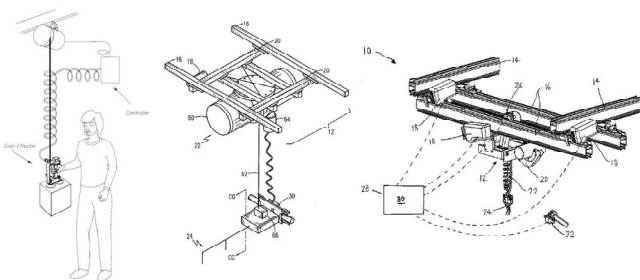


Fig. 1 Example IAD systems [1]–[3]

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An IAD is a wire-driven system that is operator controlled using a haptic interface. Traditional IAD systems determine the operator's intention by measuring the tension of the wire or using a handler. Whereas measuring the wire tension is straightforward with no additional device, the problems include a limit cycle [4] and additional process to measure the weight [5] of a heavy object as the operator's force is measured indirectly. Meantime, when using a handler, the operator's force is measured directly, making it is easy to determine the operator's intention, yet the additional handler device can be cumbersome. Traditional handlers are either grip type or band type. A grip-type handler is attached to the end of the wire and controls the system by measuring the force applied to the handle, as shown in Fig. 2 (a), whereas a band-type handler is worn on the hand and includes two sensors positioned at the top and bottom of the band to measure the force applied to handler in order to determine the operator's intention, as shown in Fig. 2 (b). The Magic Glove [6] is an example of a band-type handler, yet it only allows the operator to grasp in a horizontal posture, which can result in measurement errors due to hand rotation.
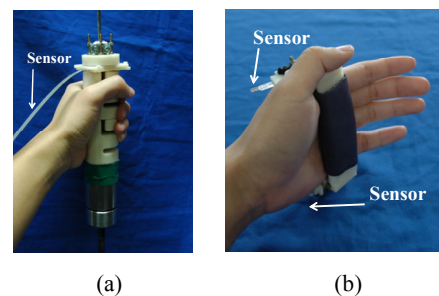


Fig. 2 Examples of handlers (a) Grip type (b) Band type

Accordingly, this paper presents an orientation-free band-type handler. Unlike the Magic Glove, the proposed orientation-free handler has no problem with rotation. The proposed system is designed as a human-in-the-loop control system to assist with lifting heavy objects. A fuzzy controller is developed using fuzzy logic, which is similar to human logic, in order to facilitate convenient control and ensure safety. Hereinafter, the proposed heavy object lifting system is referred to as WHAD (Wire-driven Human Assistive Device).

The remainder of this paper is organized as follows. The system structure and handler design are introduced in Section II, and the design of the control system is described in Section III. Experimental results for performance verification are presented

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in Section IV, and some final conclusions are given in Section V.

## II. WHAD System & Handler Interface Design

WHAD consists of a support frame, handler, controller, and actuator. The support frame is used to help lift a heavy object, and the handler transfers a sensing signal to the controller representing the operator's intention. Once the controller receives an input signal from the handler, it uses a fuzzy logic operation to output a control signal to the actuator. The actuator, which is a servo motor, then provides a force to help lift a heavy object.

The concept of the WHAD system is shown in Figs. 3 and 4. The operator recognizes the position ($p$) and velocity ($v$) of a heavy object and then applies force ($F_h$) to the handler. The controller then controls the velocity ($v_m$) of the actuator considering the magnitude and direction of the force sensed from the handler.
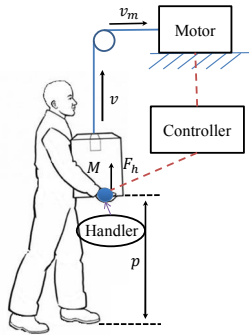


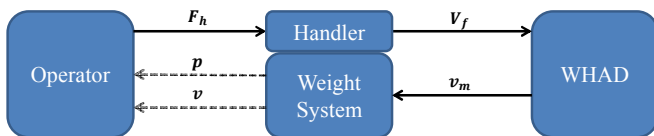Fig. 3 Schematic drawing of WHAD system



Fig. 4 System block diagram of WHAD

When the operator lifts a heavy object, the magnitude and direction of the force are sensed and the actuator generates power in an upward direction relative to the magnitude of the force. Conversely, when the operator puts down a heavy object, the magnitude and direction of the force are sensed and the actuator generates power in a downward direction relative to the magnitude of the force.

Whereas the handlers used with traditional heavy object lifting systems focus on determining the operator's intention, not much research has focused on operator convenience. For example, the hand posture changes when gripping an object according to the position of the object, as shown in Fig. 5.
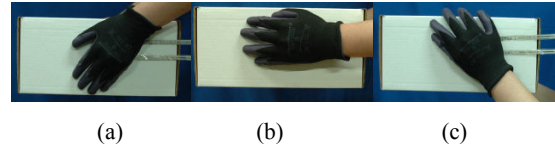


Fig. 5 Hand rotated according to relative positions of object and operator (a) Heavy object in low position (b) Heavy object in middle position (c) Heavy object in high position

Therefore, this paper proposes an orientation-free handler to facilitate hand posture changes and operator convenience. The concept is shown in Fig. 6. When the operator uses the handler, a friction force is generated between the contact surface of the handler and a heavy object, resulting in no relative movement between the handler and the heavy object. As a result, all the force applied by the operator reaches the sensor. As such, the basic principle is that the sensor data and force applied by the operator can be calculated using (1) and the up-down direction of the operator's intention can be determined using the force of the sensor data. $V_f$ is the output voltage from the FSR (force sensing resistor), $k$ is a constant that is a characteristic of the FSR sensor, and $c$ is the offset. To allow rotation of the orientation-free design shown in Fig. 6 (a), two sensors are located on the palm, along with pushingbars, as shown in Fig. 6 (b). There is also a rotatable disk, as shown in Fig. 6 (c), which maintains the sensors in the same position, even when the hand rotates. Thus, the proposed design always keeps the two sensors in an up-down position.
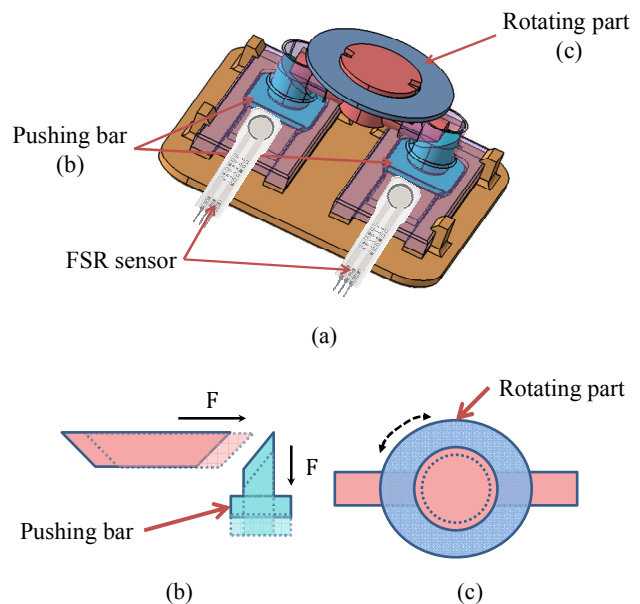
$$V_f = kF_h + c \qquad (1)$$





Fig. 6 Conceptual diagrams (a) Integrated concept (b) Pushing bar (c) Rotating part

The orientation-free handler made using a 3D printer is shown in Fig. 7. The proposed handler has no measurement problems when the operator changes their hand posture during an operation.
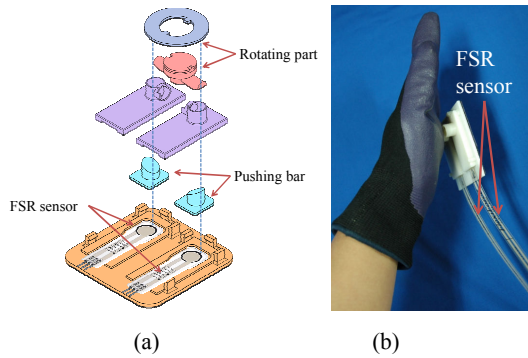
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(a)　　　　　　(b)

Fig. 7 Orientation-free handler (a) Exploded view of proposed
orientation-free handler (b) Final glove-type system

## III. CONTROL SYSTEM

The controller composition of WHAD, which cooperates with the operator to accomplish a task, is shown in Fig. 8.
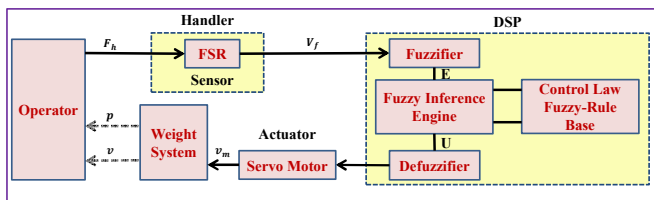


Fig. 8 Architecture of control system in WHAD

The operator's intention is predicted by sensing the force applied by the operator. The fuzzy inference at the controller then determines the velocity ($v_m$) of the actuator output.

The controller design is based on a proportional relation between the input ($F_h$) and output ($v_m$). In addition, to consider various control conditions, the WHAD design considers four cases. First, the force applied by a human is not as uniform as that applied by a machine, plus there are noises from mechanical vibration and the FSR sensor. Therefore, to determine when the operator wants to stop, the controller is designed to be insensitive to the vibration of the machine and signal noise. Second, for accurate control, a small velocity output is used when the operator applies a small force. Yet, since the human application of a small force is hard to control accurately, the controller is designed to be insensitive to variation of input force. Third, in general situations the input force and output velocity is designed to have a proportional relation. Fourth, in the case of an excessive input force, the output velocity is restricted for safety reasons. The final design including these considerations is shown in Fig. 11.

The proposed controller uses the Takagi-Sugeno (TS) fuzzy If-Then rules shown in Fig. 9. Each coefficient of the consequent parts is decided using (2) and (3), where $\alpha$ is the proportion constant, $\beta$ is the constant that connects the output function of the fuzzy control rules, $v_{m \cdot safe}$ is the maximum output velocity for safety, $F_{h \cdot small}$ is the minimum force the system reacts to, and $F_{h \cdot big}$ is the minimum force that exceeds the standard force required to make the maximum motor velocity output. The membership functions of $F_h$ are shown in

Fig. 10. When setting the constant values as $v_{m \cdot safe} = 100\%$, $F_{h \cdot small} = 3N$, and $F_{h \cdot big} = 17N$, the results are as shown in Fig. 11.
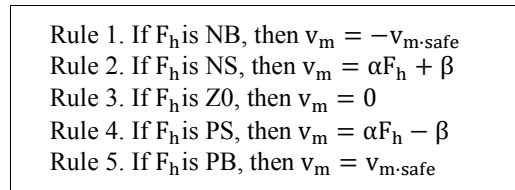
Rule 1. If $F_h$ is NB, then $v_m = -v_{m \cdot safe}$
Rule 2. If $F_h$ is NS, then $v_m = \alpha F_h + \beta$
Rule 3. If $F_h$ is Z0, then $v_m = 0$
Rule 4. If $F_h$ is PS, then $v_m = \alpha F_h - \beta$
Rule 5. If $F_h$ is PB, then $v_m = v_{m \cdot safe}$

Fig. 9 Fuzzy rules for WHAD controller

$$\alpha = \frac{v_{m \cdot safe}}{F_{h \cdot big} - F_{h \cdot small}} \tag{2}$$
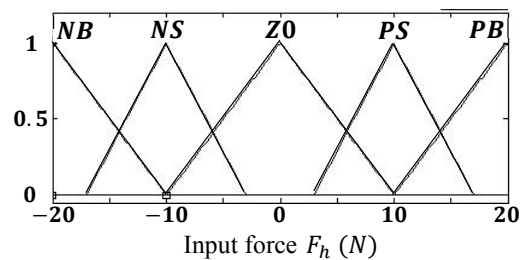
$$\beta = \alpha F_{h \cdot small} \tag{3}$$



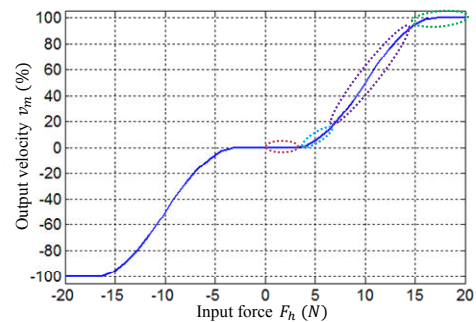Fig. 10 Membership function for variable $F_h$



Fig. 11 Input versus output in WHAD controller

## IV. EXPERIMENTAL RESULTS

The effectiveness and performance of the proposed WHAD system were evaluated using the experimental set-up and parameters shown in Fig. 12 and Table I, respectively.
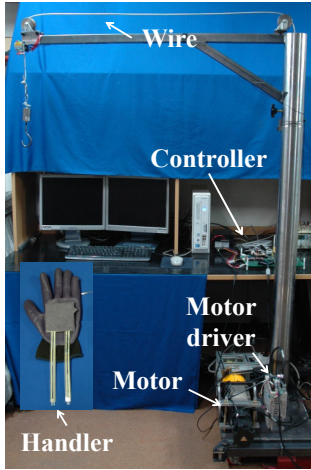
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Fig. 12 Image of WHAD

TABLE I
WHAD PARAMETERS

| Component | Specification |
|---|---|
| Main Processor (DSP) | TMS320F28335 |
| | 32bit integer C28X Core + FPU |
| | 150MHz / 150MMAC / 300MFLOPS |
| | RAM : 68KByte, FLASH : 512KByte |
| Force Sensor (FSR) | A201 series |
| | Standard Force Range : 0-111N |
| | Size : 14mm * 197mm * 0.208mm |
| | Sensing Area : 9.53mm diameter |
| Actuator | SGMJV-08ADA2C |
| | Rated Output : 750W |
| | Power Supply Voltage : 200 VAC |
| | Max. Speed : 6,000rpm, Rated Speed : 3,000rpm |
| | Instantaneous Peak Torque : 8.36N·m |
| | Rated Torque : 2.39N·m |
| | Serial Encoder : 20 bit incremental |
| Power Source (SMPS) | 1CH : 24V (for holding brake) |
| | 4CH : 5V, 12V, -12V, 24V (for control unit) |

### A. Heavy Object Moving Experiment

Fig. 13 shows the experiment of the lifting up and setting down a heavy object.



Fig. 13 Experimental scenes

### B. Quantization of Experiment Data

Various experiments were performed to quantify the assisting power of the WHAD system. The output ($V_f$) of the sensor relative to the force applied by the operator is shown in Fig. 14. The constant values of (1) calculated using this data were k=0.02646 and c=0.0022.
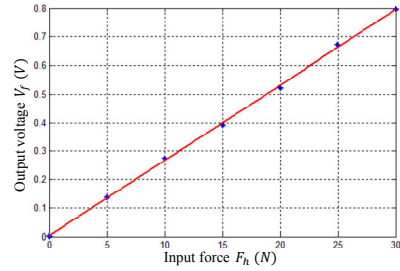


Fig. 14 Operator force versus ADC value

### C. Analysis of Experiment Results

The analysis examined the force variance when the operator lifted and set down a 20kg object, as shown in Fig. 15. When the operator lifted the object, the maximum force, 2kgf ($\approx$20N), was measured by the sensor on the operator's hand, whereas the maximum force, 1.5kgf ($\approx$15N), was measured when the operator set down the object. In this situation, the output ($v_m$) of the WHAD system is shown in Fig. 16. When the operator was not moving a heavy object, the controller removed the noise and slight forcemeasured from the sensor to maintain 0 outputs. When the operator then wanted to use the WHAD system, the controller rapidly controlled the WHAD system following the operator's intention. The controller exhibited no overshoot or unstable vibration phenomena. As shown in Fig. 17, fine control was possible by making a small output based on a small input force. Thus, the experimental results showed that the operator was able to use a force smaller than 20N to lift and set down a heavy object when using the WHAD system.
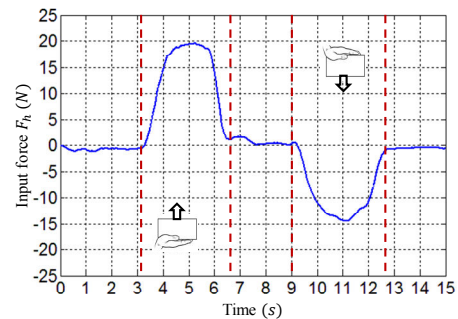


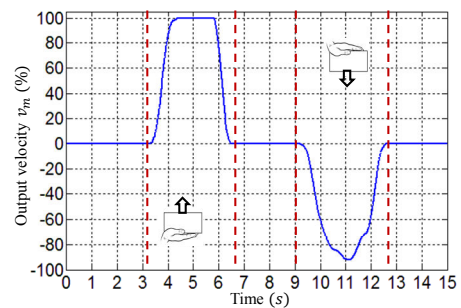Fig. 15 Example of operator's force pattern



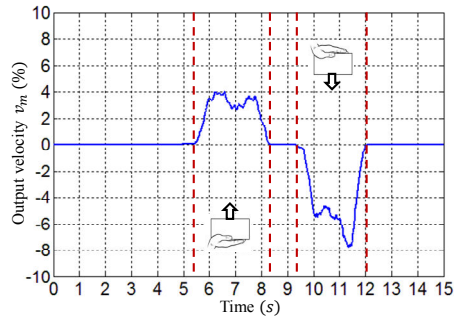Fig. 16 Output fluctuation of WHAD system

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Fig. 17 Very slow velocity for precise control

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## V. Conclusion

This paper presented the WHAD system with an orientation-free handler and fuzzy controller design. Experiments confirmed that the WHAD system required much less force and was convenient when lifting and setting down a 20kg object.

With aging populations and smaller families, the number of elderly people living alone is rapidly increasing worldwide. Plus, many elderly people are employed in agriculture and fishing, and experience physical difficulties due to heavy lifting. Therefore, as a solution, the proposed WHAD system is an assistive system that can be used for lifting and other health-related applications in homes, hospitals, and various industries.

## Acknowledgment

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