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A Novel Arm-Wrestling Robot Using Motion Dependant Force Control

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1. Introduction

In recent decades, aging population of most advanced countries has increased sharply, and elderly health care has become economically a big social issue. One way to cope with this problem is to introduce various service robots such as an arm-wrestling robot proposed in the article into our daily lives, which are able to promote elderly health and to save elderly welfare cost.

For successful execution of many tasks of service robots (Engelberger, 1989) such as robotic arm-wrestling, control of interacting force between a robot and the environment is crucial. Several interacting force control strategies have been developed during the past two decades (Whitney, 1987; Gorinevsky et. al., 1996; Siciliano & Villani, 1999; Natale, 2003), which can be classified into two groups; indirect force control without explicit closure of a force feedback loop, and direct force control with explicit closure of a force feedback loop (Natale, 2003).

Indirect force control includes compliance (or stiffness) control (Salisbury & Craig, 1980; Mason, 1981) and impedance control (Hogan, 1985; Anderson & Spong, 1988), in which the position error is related to the contact force through a mechanical compliance or mechanical impedance between the robot and the environment. On the other hand, direct force control includes hybrid position/force control (Raibert & Craig, 1981) and inner/outer motion/force control (Caccavale et al., 2005), in which actual force is measured using a force sensor and then is controlled via direct force feedback. If a detailed model of the environment is available, the hybrid position/force control can control position along a constrained direction and force along an unconstrained direction using a selection matrix. If a detailed model of the environment is not available, inner/outer motion/force control can control force and motion, in which outer force control loop is closed around the inner motion control loop.

These force control strategies generally assume that the environment is fixed in space. However, there are applications that the environment being contacted by the robot is no longer fixed in space, but is moving. In this case, contacting force control is much more challenging problem compared to the fixed environment case. For example, in robotic arm-wrestling considered in this article, the environment should be modeled as a moving object with compliance, viscous friction and inertia.

In the reference (Gorinevsky et al., 1996), the problem maintaining contact force with a moving object was considered, and the force regulation control of manipulator motion was treated as a motion control with imposed mechanical constraints. However, some application such as robotic arm-wrestling doesn't require motion control but pure force control, and require different force generation scenario according to the present position and velocity situation.

Recently, there have been other efforts in the emerging field of human-centered robotics, which focuses on safety-critical applications such as medical robots, service robots and entertainment robots. These human-centered robotic systems closely interacting between robots and humans require an additional issue, dependability in addition to conventional force control performance (Zinn et al., 2004; Bicchi & Tonietti, 2004).

In this article, we propose a force control logic for the moving environment (i.e., moving object), called motion-dependent force control. Position and velocity information of the moving object as well as interacting force information are fed back and affect actual force generation in the proposed control logic. Differently from the hybrid force control, force, position and velocity are measured and driven at the same direction. The proposed force control logic is applied to an arm-wrestling robot recently developed in our laboratory. Also, we present a user safety issue at the arm-wrestling robot.

Section 2 introduces an arm-wrestling robot developed in our laboratory. In section 3, the proposed force control logic is presented, and then application results of the proposed force control logic to the arm-wrestling robot are described in section 4. Discussions and conclusive remarks are in the final section 5.

2. A novel arm-wrestling robot

An arm-wrestling robot called Robo Armwrestler (Fig. 1) has been recently developed in our Intelligent Control and Robotics Laboratory, Konkuk University, in order for the elderly to help to keep their muscular strength, and to improve the quality of life of them physically and mentally. This project has been supported financially by the Korean government.

The Robo Armwrestler has salient features. Namely, it generates automatically the force level appropriate to each person after sensing the human arm-force at the early stage of the match, and therefore any person with either a strong or weak arm-force can enjoy arm wrestling without any parameter changes. Its generated force profile varies with each match, so one person can enjoy arm wrestling with the robot for a long time without becoming bored. The winning average of the robot is determined randomly at the start of the match, but the robot measures the person's will to win during the match, and the result influences the winning average of the robot. For example, the robot's arm-force becomes weaker and weaker, and the winning probability of the human increases if the human tries to stand out to win the match for a long time. The robot recognizes a human's approach and begins to talk, such as "Hello, welcome to the Robo Armwrestler! If you want to try arm wrestling, please sit down on the chair." and also automatically recognizes the human's sitting on the chair, and guides them on how to play and enjoy arm wrestling. The facial expression of the avatar changes synchronously according to arm wrestling situations.

The arm-wrestling robot is composed of an arm-force generation mechanism, a force control system, and an intelligent game scenario generation engine.

The arm-force generation mechanism comprises a servo motor, a position/velocity sensor, a speed reducer, a torque sensor, three inclinometers, a mechanical arm, and an adapter with

a mechanical stopper. The electric servo motor provides necessary torque according to motor control input signals, and the position/velocity sensor detects angular position and angular velocity of the motor. An incremental encoder is selected as the position/velocity sensor for high resolution. The speed reducer decreases the speed and increases the torque of the motor. A harmonic drive is selected as the speed reducer instead of conventional gears that have large backlash, and thus cause trouble in torque control performance. The torque sensor detects the torque acting on the mechanical arm, which is installed between the speed reducer and the mechanical arm. The torque sensor should have reasonable resolution in order to get a reasonable force control performance. The adapter with a mechanical stopper is utilized to restrict the angle range of motion of the mechanical arm in order to guarantee safety of the user. The adapter is further utilized to set the initial absolute angle of the mechanical arm by means of low speed control of the motor. The initial setting of the absolute angle of the arm can also be achieved redundantly by means of using multiple inclinometers (Kang et. al., 2004).



Fig. 1. The developed arm-wrestling robot. The President of Korea, Roh Moo-hyun arm-wrestled against Robo Armwrestler at the 2005 Future Tech Korea Exhibition (COEX in Seoul).

Two ultrasonic sensors are attached at the right and left sides on the front of the table, and detect a human's approach within a prescribed range of angles near the arm-wrestling robot. Ultrasonic sensors have an advantage of high noise immunity compared to other types of sensors, and can easily measure the distance of an approaching human under any circumstances. One photoelectric sensor using infrared rays detects a human sitting on a chair. In order to guide the player, the display monitor and speakers are prepared at an appropriate position of the table.

Control hardware is comprised of a CPU, a memory, an amplifier, a logic circuit, a pulse generation part, and output ports. The CPU produces motor control input using the control program and the feedback signals, and produces voice and image signals. The memory stores the control program including control logic and scenarios. The amplifier amplifies the low level voltage signal coming from the torque sensor, and achieves signal conditioning. The logic circuit conditions the feedback signal from the position/velocity sensor, and the pulse generation part produces a pulse signal for the ultrasonic sensors. Voice speakers and a display monitor are driven by the CPU through output ports.

Torque sensor, inclinometer, photoelectric sensor, and ultrasonic sensor signals are converted to digital signals through A/D converters, and transmitted to CPU. Encoder signals are transmitted to CPU directly through digital input channels. Motor driving signals are converted to analog voltage through a D/A converter, and transmitted to the motor driver.

When the CPU is down, the D/A converter can still output the last signal of the motor control input, and thus a dangerous situation can occur if the electric power is applied to the motor again. To resolve this problem, the CPU transmits an initialization completion signal to the motor power control part through a D/A converter, and sends 0 value to the motor driver through the D/A converter when the initialization procedure is completed (the initialization procedure starts when the main switch is pressed on). The motor power control part turns on the mechanical relay (MR) to supply the electric power to the motor according to the output signal of the solid state relay (SSR), which in turn is actuated by the initialization completion signal.

User safety is thus guaranteed even if the motor power switch is turned on before completing the initialization procedure or at abnormal conditions of the control system since the electric power is not transmitted to the motor.

When using the incremental encoder as the position/velocity sensor, we initially set the absolute zero degree angle of the mechanical arm using the mechanical stopper and velocity feedback control. More specifically, the control part slowly drives the motor clockwise or counterclockwise using position feedback control, and measures torque value of the torque sensor. If the measured torque is bigger than the threshold value, then the control part sets the present angular position as the specified degree of absolute angle, since the big measured torque implies that the mechanical stopper hit the stopper seat block.

The intelligent game scenario generation engine generates an appropriate force profile for each match, using a human's maximum force, a human's force pattern, time duration, a human's will to win, and randomness. The winning or losing is not predetermined, but varied online according to the pattern of the game progression.

For a few seconds in the early stage of the game, the engine detects the human's maximum force according to the procedure. The system increases force up to the specified value with a parabolic fashion for a short time, and then the robot measures arm velocity at regular intervals for the next few seconds. If the velocity is positive, then the robot increases the force until the velocity becomes negative, and memorizes the force value.

To realize unpredictable and intelligent game patterns, we adopt a random number and a value called *will point* that quantifies the will of the arm-wrestler to win the match. If the will point is near 100, the user is considered to have a strong desire to win the match. If the will point is near 0, the user is considered to have a weak desire to win the match. The will point is calculated by

$$\text{will point} = (\text{average arm-force during one sub-scenario}) / (\text{maximum arm-force of the user}) \times 100 \quad (1)$$

The game scenario is composed of several sub-scenarios. If a sub-scenario is selected by means of random number, the robot decreases or increases the force during randomly determined intervals of time. During these intervals of time, human force is measured and averaged in order to calculate the will point. As soon as the execution of the sub-scenario is completed, the next sub-scenario is immediately generated online at that instant.

Arm wrestling progression is affected by the will point and the pre-specified probability. For example, if the obtained will point is 86, the class of win, draw, or defeat scenario is

determined according to winning probability with 8 %, drawing probability with 90 %, and defeat probability with 2 %. This class determination is conducted using a random number 0 ~ 99, that is, the generated random numbers 98 and 99 imply the defeat class, random numbers 8 to 97 imply the drawing class, and random numbers 0 to 7 imply the winning class.

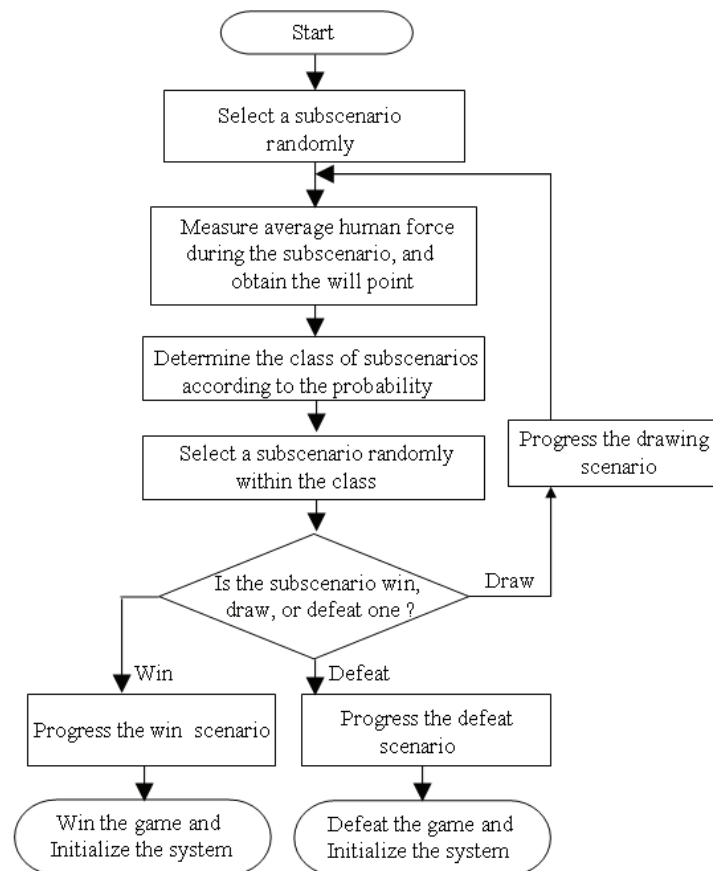


Fig. 2. Flowchart of the progression of robotic arm wrestling. The winning average is determined by random numbers and will points.

Using another random number, we select a sub-scenario randomly within sub-scenarios of the determined class. If the selected sub-scenario is a drawing one, then the will point is recalculated after the sub-scenario ends, and the above procedure is repeated. If the selected sub-scenario is a win or a defeat one, then the win or defeat sub-scenario is progressed, and the human wins or defeats, and the arm wrestling ends. Finally, the arm-wrestling system is initialized for the next match. Fig. 2 shows a simplified flowchart for the progression of robotic arm wrestling.

In an idle situation, the robot plays music, and waits for a person. As a person approaches the robot, the system automatically detects his approach, greets him, and encourages him to arm-wrestle. If the person sits down, the robot guides him to start the game

The actuation of the robotic arm-wrestling is composed of four steps. The first step is to initialize the arm-force generation mechanism and the control system, and to achieve the setting of an initial angle of the mechanical arm. The second step is to detect a human's approach to the arm-wrestling robot using ultrasonic sensors, and the human's sitting on the chair using a photoelectric sensor. The third step is to measure the maximum arm-force of

the user during a specified time interval based on the feedback signal coming from the torque sensor. The fourth step is to generate an intelligent arm-wrestling scenario, and to control the robot arm according to the proposed force control logic.

The winning sub-scenario implies a significant decrease of torque command value, the losing sub-scenario implies a significant increase of torque command value, and the drawing sub-scenario implies a small increase, a small decrease, or no change of torque command value.

The sub-scenario generated online is characterized by force increment, rising time, and maintaining time. These three values are determined using random numbers and the will point. The force increasing or decreasing in the sub-scenario is achieved by smooth polynomial curves.

3. Motion-dependant force control

For realizing robotic arm-wrestling, the arm-wrestling robot should increase arm-force rapidly in order to prevent from being lost easily when the human arm-wrestler tries to turn over the robot arm abruptly. For this purpose, the existing force control strategies such as compliance control, impedance control, hybrid position/force control, or inner/outer motion/force control, are not appropriate.

Conventional force control strategies for robot manipulators generally consider the situation that the environment is fixed in space as shown in Fig. 3(a). But there are situations that the environment being contacted by the robot is moving, and can be modeled as a moving object as shown in Fig. 3(b).

In the case of the moving environment, the motion of the moving object affects the contact force between the robot and the environment, and thus it should be considered quantitatively for the design of force control system. There could be two different situations. One situation is to regulate the contacting force constantly even if the environmental object is moving, and the other situation is to generate and control different interaction forces depending on current motions (that is, positions and velocities).

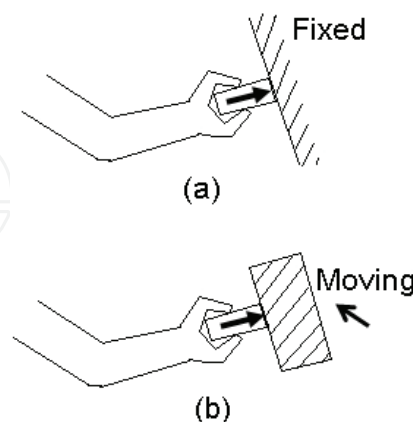


Fig. 3. Schematic models for fixed and moving environment.

We propose a control logic, called motion-dependent force control, for the latter situation. Being different from stiffness control, impedance control, hybrid position/force control, and inner/outer motion/force control, the motion-dependent force control logic does not possess explicit position or velocity feedback loops and does not control the position or

velocity of the robot arm directly. Instead, the measured position and velocity information are used only for generation of force commands of the force control loop.

The block diagram of the proposed force control scheme is shown in Fig. 4. The control system receives feedback signals of actual position, velocity, and force, and calculates force command using feedback signals and other operation requirements. The system then controls the mechanical arm by means of generating the motor control input according to the proposed force control law. The force control law in the block diagram could be a PID type control law or other advanced control laws.

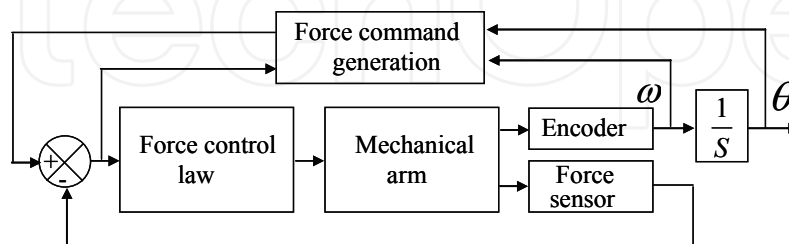


Fig. 4. Simplified block diagram of the motion-dependent force control system.

Force command $\tau_{command}$ is generated by the following formula in the proposed force control logic.

$$\begin{aligned}\tau_{command} &= \tau_{basic_operation} + \Delta\tau \\ \Delta\tau &= \Delta\tau_v + \Delta\tau_p \\ \Delta\tau_v &= K\omega\end{aligned}\quad (2)$$

where $\tau_{basic_operation}$ is a part of the force command demanded from the basic operation requirement, for example, game scenario in the robotic arm-wrestling, and $\Delta\tau$ is an added term demanded from the current motion. $\Delta\tau$ is composed of a correction term $\Delta\tau_v$ affected by the current velocity of the robot arm, and a correction term $\Delta\tau_p$ affected by the current position of it. In robotic arm-wrestling, for example, $\Delta\tau_v = K\omega$, and the value K is given from the gain scheduling table according to the actual angular velocity ω of the robot arm. $\Delta\tau_p$ affects $\tau_{command}$ to be zero whenever the robot arm reaches the limit angles set up initially in either direction.

In the arm-wrestling robot considered in the article, $\tau_{basic_operation}$ is given by the intelligent game scenario described in the previous section. More specifically, $\tau_{basic_operation}$ is determined on-line by the random combination of force magnitude, force-sustaining time, human's reaction pattern after detecting human's maximum force, and then by smoothing stepwise force command generated. One sample force command generated in this procedure is shown in Fig. 5.

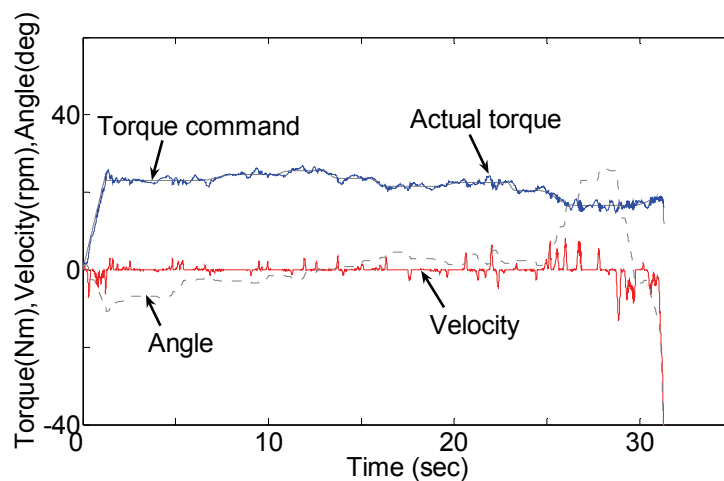
4. Experimental results

To order to demonstrate the validity of the proposed force control logic, we applied it to the arm-wrestling robot and conducted force control experiments. Force control performance is

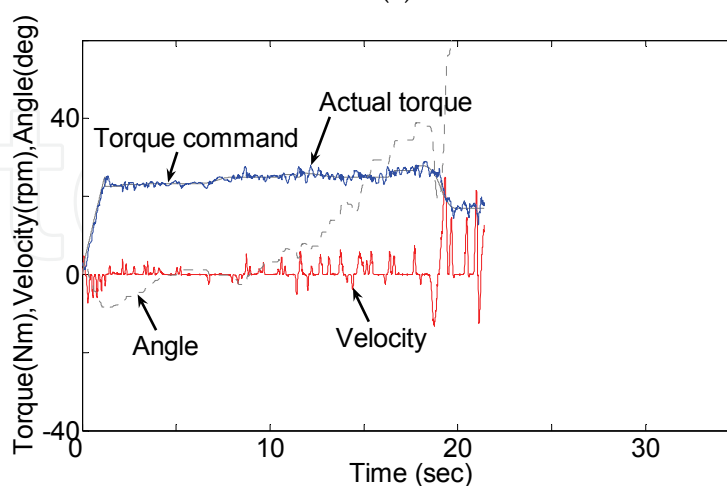
mainly dependent on the accuracy of feedback signals, and real-time control capability, including the accuracy of sampling time, and the force feedback control logic itself.

Linux and RTAI (real-time kernel) have been adopted for the operating system of the arm-wrestling robot. When Linux and RTAI were implemented at desktop PC with Pentium IV 2.8GHz, timing errors less than ± 0.02 ms occurred for generating 5 ms timer interrupts. However, Window XP had roughly ± 1 ms latency when we executed the same program with the same PC platform.

Fig. 5 shows experimental results of the proposed motion-dependent force control when a 72-year-old woman played against the arm-wrestling robot. In the figures, blue solid lines imply torque commands, grey solid lines imply actual torques, red solid lines do angular velocities, and grey dotted lines do arm angles. From these graphs, we see that force command is generated intelligently using actual velocity and position information, and the generated scenario information. Furthermore, actual force reasonably tracks the force command by the proposed force control logic. Fig. 4 also shows that force pattern and elapsed time for each match are different from match to match even if the same person plays.



(a)



(b)

Fig. 5. Robotic arm-wrestling results of a 72-year-old woman. (a) a case where the woman won the game after the elapse of 31 seconds, (b) a case where the woman lost the game after the elapse of 21 seconds.

Fig. 6 shows a result of the match between a strong 25-year-old youth and the arm-wrestling robot, and Fig. 7 illustrates a match between a 10-year-old child and the arm-wrestling robot. As soon as the youth finished the match of Fig. 6, the child began the match shown in Fig. 7. Although the youth produced roughly 50 N·m, and the child roughly 20 N·m, the arm-wrestlings proceeded smoothly without changing any parameters of the robot.

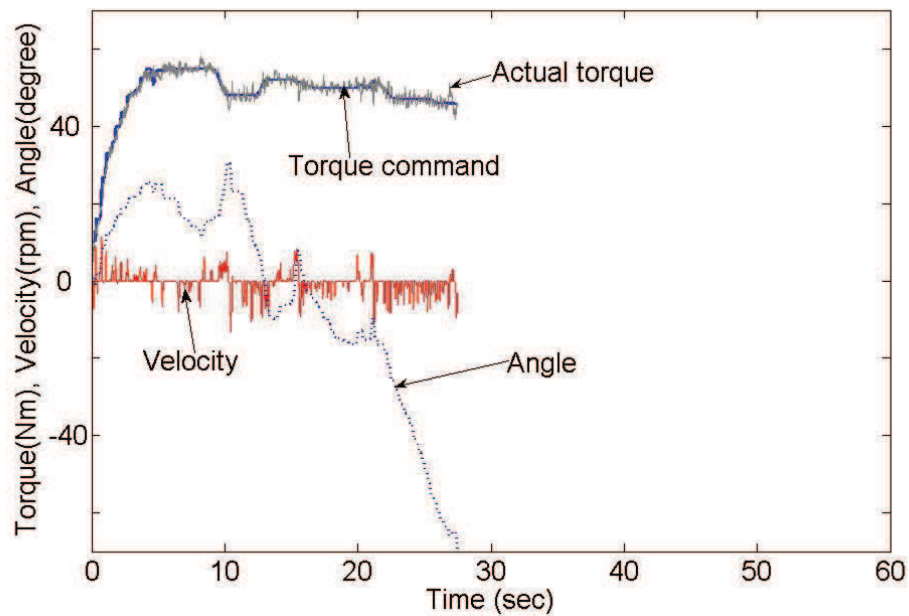


Fig. 6. Robotic arm-wrestling result of a 25-year-old youth who lost the game after the elapse of 28 seconds.

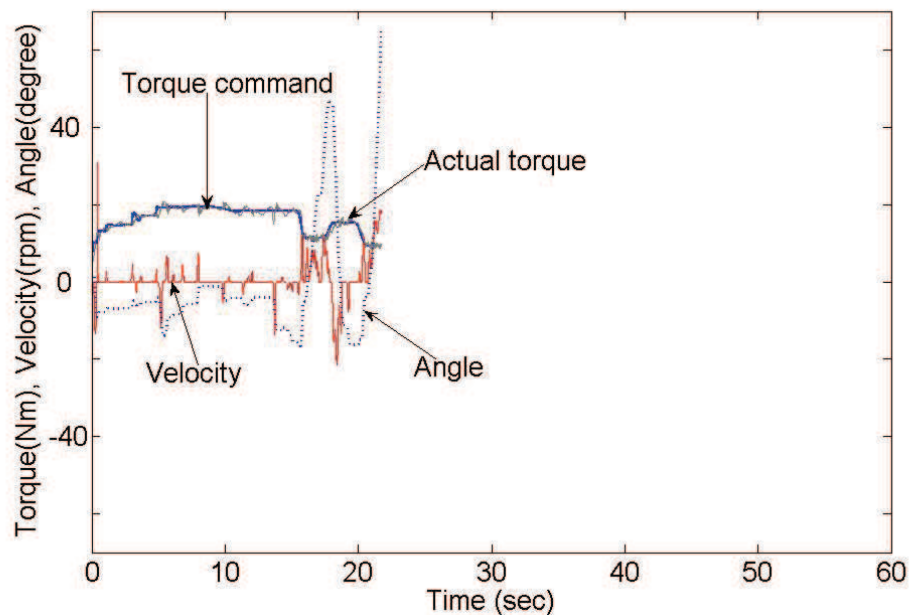


Fig. 7. Robotic arm-wrestling result of a 10-year-old boy who won the game after the elapse of 23 seconds.

Table 1 shows the elapsed time and winning/losing probability of each match when one user played arm wrestling 26 times with the arm-wrestling robot. From Table 1, we see that the elapsed time for a match varies each time, and the result of the match also varies each time, so that the enjoyment of the arm wrestling can be maintained for a long time without being bored. Table 2 summarizes results when two users played arm wrestling 26 times each with the Robo Armwrestler. Table 2 shows that the first user has 63 % of human's winning probability and the second user has 75 % of human's winning probability.

Operation experiences at the laboratory and Exhibitions have revealed that the proposed force control logic is appropriate for controlling contact force between the robot and the moving object, especially for controlling contact force between the arm-wrestling robot and the human arm-wrestler. The arm-wrestling robot with the proposed motion-dependent force control logic has generated intelligent scenarios unpredictably and reliably, and controlled the robot arm-force properly so that the human arm-wrestler feels as if he is arm-wrestling against a human. When the Robo Armwrestler was introduced to the public at the Future Tech Korea Exhibitions, it has been spotlighted in the mass media.

5. Conclusion

In this article, a novel arm-wrestling robot and a motion-dependent force control logic applicable to controlling contact force between a robot and a moving environment (i.e., moving object) have been proposed. In the motion-dependent force control logic, position and velocity information of the moving object as well as interacting force information are fed back and affect actual force generation and control. However, being different from stiffness control, impedance control, hybrid position/force control, and inner/outer motion/force control, the motion-dependent force control does not possess explicit position or velocity feedback loops, and does not control the position or velocity of the robot arm directly. Instead, the measured position and velocity information are used only for generation of force commands of the force control loop.

To demonstrate the validity of the proposed force control logic, we have applied it to the arm-wrestling robot recently developed in our laboratory, and showed the force control performance experimentally.

The experimental results and operational experiences at the Exhibitions have verified that the proposed force control logic is well suited for controlling contact force between the robot and the moving object, especially for controlling contact force between the arm-wrestling robot and the human arm-wrestler.

In this article, we have presented the system design, implementation, force feedback control, and generation of intelligent arm-wrestling scenarios of an arm-wrestling robot. Although the robot works as expected with the designed autonomy and reasonable control performance, we plan to further pursue research in order to build the arm-wrestling robot capable of recognizing facial expressions of the human using a webcam, and thus emotionally communicating with the human player. Moreover, we plan to add more degree-of-freedom for more human-like motion, and to eventually integrate arm-wrestling function into a humanoid robot.

Trial	Elapsed time (sec)	Result	Trial	Elapsed time (sec)	Result
1	11.0	Win	14	17.6	Lose
2	14.0	Win	15	14.5	Lose
3	20.0	Win	16	7.8	Lose
4	47.0	Lose	17	12.0	Lose
5	20.0	Win	18	11.5	Win
6	23.2	Win	19	23.4	Win
7	13.6	Win	20	8.4	Lose
8	11.7	Win	21	14.7	Win
9	14.5	Win	22	6.4	Win
10	22.2	Lose	23	18.8	Lose
11	12.1	Win	24	15.1	Lose
12	9.5	Win	25	13.6	Win
13	12.1	Lose	26	19.5	Win

Table 1. Elapsed time and match results when one user played 26 times with the arm-wrestling robot.

	Elapsed time average	Percentage of human wins
Person 1	17.0 sec	63 %
Person 2	14.0 sec	75 %

Table 2. Results when two users played 26 times each with the Robo Armwrestler

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The aim of this book is to provide new ideas, original results and practical experiences regarding service robotics. This book provides only a small example of this research activity, but it covers a great deal of what has been done in the field recently. Furthermore, it works as a valuable resource for researchers interested in this field.

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