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Double Loop Control Strategy with Different Time Steps Based on Human Characteristics*

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Abstract— **This paper proposes a cooperative control strategy in consideration of the *force sensitivity* of human. The strategy consists of two loops: one is the intention estimation loop whose sampling time can be variable in order to investigate the effect of the sampling time; the other is the position control loop with fixed time step. A high sampling rate is not necessary for the intention estimation loop due to the bandwidth of the mechanoreceptors in humans. In addition, the force sensor implemented in the robot is sensitive to the noise induced from the sensor itself and tremor of the human. Multiple experiments were performed with the experimental protocol using various time steps of the intention estimation loop to find the suitable sampling times in physical human robot interaction. The task involves pull-and-push movement with a two-degree-of-freedom robot, and the norm of the interaction force was obtained for each experiment as the measure of the cooperative control performance.**

I. Introduction

In physical Human-Robot Interaction (pHRI), the major issues are how to detect human intentions and how to assist them while complying with their intentions [1]. In order to extract the human intention, various sensor systems were suggested [2]-[5]. The force sensor among those is widely used due to the reliability compared to that of bio-electrical sensors such as electromyography [6] and electroencephalo -graphy [7]. Robot detects the interaction force as an intention of the human, and follows the human motion using an impedance control or an admittance control [8]-[13]. These control laws are well known control architectures to make compliance with an unknown environment using force sensor. However, the sensed force is not a pure intention of the human. It involves the intended force of human as well as a reaction force induced from the robot. The reaction force depends on the velocity of the motion, and the inertia of the payloads.

In order to reduce the effects of the robot dynamics, variable impedance (or admittance) controls based on the position controller were proposed [9]-[12]. Wang et al. suggested online parameter estimation using a recursive least-squares method to realize an adaptive admittance filter [9]. Unfortunately, humans easily adapt to the movement of robots by adjusting their arm impedance [12]. In other words, the overall dynamics does not depend primarily on the robot impedance but on the human characteristics. Previous researches focus on the biomechanics of the human without much consideration of the physiological characteristics of the human such as reaction time and sensitivity. The reaction time of the human is defined as the elapsed time between a stimulus and the response to it [15]. In the case of braking of a car, the stimulus is an obstacle detected by the driver's vision, and the response is his legs stepping on the brakes. In pHRI, the reaction time is related to the sensitivity of the mechanoreceptor in human body in contact with robot. The force sensitivity of the human has analogy with the bandwidth of the force sensor in robot control. Although the control loop of the human and that of robot are similar, as shown in Fig. 1, their sampling times are different. The sampling time of the robot control loop is on the order of a few milliseconds (i.e. 1 ms or 2 ms), while the reaction time of the human is on the order of tens or hundreds of milliseconds due to the limitation of muscle strength and neural delay [16].

Fast sampling time of the force sensing loop can make the overall dynamics noisy. Since the robot motion is not predefined in the cooperative control scheme, the interaction force, including the reaction force and the sensor noise is unpredictable. To investigate the effects of the sampling time of the force sensing loop during the movement with a robot, this paper proposes a double loop control strategy with different time steps, as shown in Fig. 2: one loop is the intention estimation loop with variable time step in consideration of the force sensitivity of the human; and the other loop is the position control loop with fixed time step. This paper is organized as follows: In Section II, the double-loop control strategy with two time steps is explained; Section III performs the experiments while varying the sampling time; Section IV discusses the results and compares them with the information from literature; finally, Section V is the conclusion of the proposed strategy

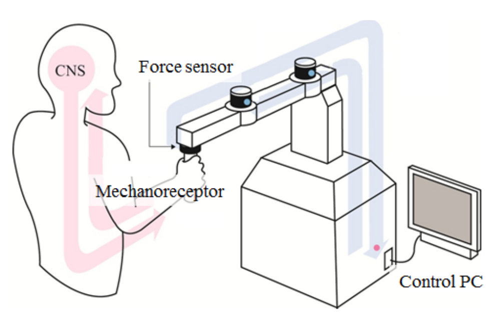

Fig. 1. Movement is triggered from the CNS, and stimulus is continuous from the robot.

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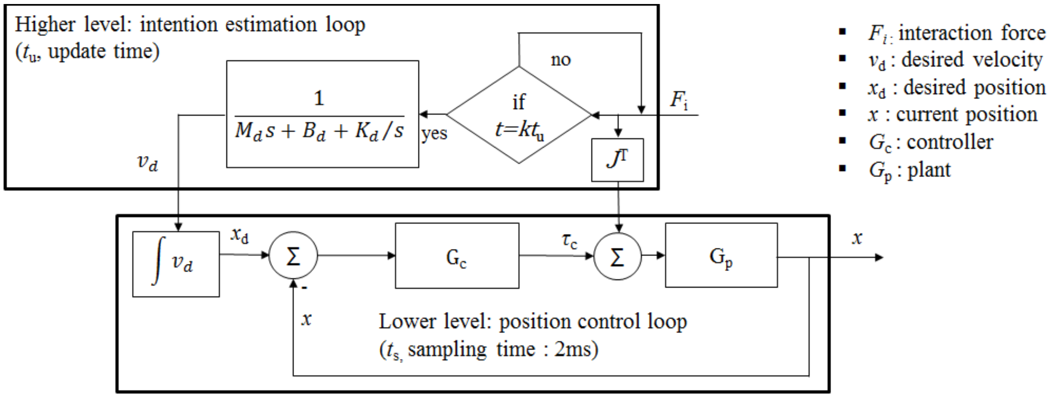

Fig. 2. Overall block diagram of control strategy

II. CONTROL STRATEGY

This section explains the control strategy in consideration of the force sensitivity of the human. Overall double loop block diagram with two time steps is shown in Fig. 2. The higher level loop is the intention estimation loop using force-feedback, and the lower level loop is the position control loop following the motion estimated from the higher level loop.

The sampling times of force sensing loop and position control loop are the same as in previous pHRI control strategy [9]-[12]. The human cannot move fast but is intelligent, while the robot is not intelligent but fast in the movement including sensing and actuating. In addition, because the force sensor implemented in the robot is sensitive to noise, the high-speed sampling can induce the vibration. We assume that the suitable update time of the intention estimation loop is related to the *human characteristics*. In order to investigate the effect of the sampling time of force sensing, the update time step size is designed to be variable. The update time (t_u) means the update period of the higher level force sensing loop. The interaction forces (F_i) can be obtained at every sampling time. The force value obtained at the update time was used to estimate the desired velocity (v_d) based on general admittance control schemes, as expressed in (1). The impedance characteristics of the human during movement with a robot were investigated in [12], [17]. Rahman et al. reported that the inertia and the stiffness were ignored after 0.4 second [17]. This means that a pure damping dynamics model could be possible in point-to-point movement [10]. The value of 18.0 (Ns/m), which is in the range of 13.4~29.5 (Ns/m) based on [18], was used in experiments.

The time step of the lower level loop is the fixed sampling time which is usually 1 ms or 2 ms for general position controllers. In this paper, a PID controller with 2 ms was used to follow the desired velocity. The desired position was calculated from (2), and imported to the position controller at every sampling instance. Then the desired velocity is updated at each time step of the higher level loop and the desired position is updated at each time step of the lower level, sampling time.

$$\frac{v_d(s)}{F(s)} = \frac{1}{M_d s + B_d + K_d/s} \tag{1}$$

$$x_d = \mathrm{x} + v_d dt \tag{2}$$

where, dt denotes the sampling time, x indicates the current position, and v_d indicates the desired velocity.

III. EXPERIMENTS

For the simplification of general human robot interaction, one-dimensional back-and-forth movement with a 2DOF planar robot was chosen. Multiple experiments were performed while varying the update time step.

A handle was attached to the end-effector of the robot. The lengths of the links $l1$ and $l2$ are 0.40 *m* and 0.25 *m*, respectively. At joint 1, an AC servo motor (Mitsubishi, HC-KFS43) with a 400W power was used to transmit power through a harmonic drive with a gear reduction ratio of 100:1. At joint 2, a motor (Mitsubishi, HC-KFS23) with a 200 W power were used with a gear reduction ratio of 80:1. Each joint has an encoder with the resolution of 131072 pulses/rev. The implementation of the controller was made in QNX, a real-time operating system, with a sampling time of 2 ms. A commercial force sensor (ATI, Gamma SI-130-10, bandwidth: 1400 Hz, resolution: 0.0125 N) was used to measure the interaction forces.

The independent variable of the experiments was the update time of intention estimation loop (2 , 6, 10, 20, 30, 40, 50, 60, 70, 80, and 100 ms), and the dependent variables was the norm of the interaction forces. The final goal of this control strategy is to assist humans with their intended motion. The quality of the control strategy depends on the magnitude of the interaction forces. Zhang et al. used the norm of the interaction force as the measure of transparency [3]. For the comparison of the norm of the interaction force in the case of each time step, the direction and velocity of the movements should be constrained to an identical task. The movement was along the y direction, as shown in Fig. 3. Since the velocity of the movement affects the interaction force, every experiment should be performed in the same speed condition. To constrain the velocity of movement, a moving target was implemented on the tabletop using a computer display. A laser pointer was attached on the bottom of the handle, and subjects were asked to move the handle pointing to the moving target, as shown in Fig. 3. The average speed of the movement is 13 cm/1.5 seconds.

In multiple experiments, subjects grasp the handle and apply the force in the y direction. Subjects were asked to pull and push the handle to track the moving target. Since the human easily adapts to the movement with a robot, as mentioned in the introduction, the order of time step sizes is randomly arranged in the experiments. Two subjects participate in the experiment. Subject A is male, 26 years old, and 65 kg. Subject B is male, 24 years old, and 68 kg.

At first, the interaction force during the pull-and-push movement without control was checked, as shown in Fig. 4. In this case subjects could not follow the moving target due to the friction from the large gear reduction ratio. A large interaction force up to 50 N was needed to complete the task. Experiments with the proposed control strategy were then performed following the experimental protocol. The protocol (KH2010-25) was approved by the Institutional Review Board at the Korea Advanced Institutes of Science and Technology (KAIST). Written informed consent and assent were obtained from the subjects. The interaction force during the pull-and-push task considerably decreased, as shown in Fig. 5 (top) compared to the Fig. 4. Since the position controller had been well tuned, the position of the handle was well tracked to the desired position, as shown in Fig. 5 (bottom). The norm of force data of subject A and of subject B is as shown in Fig. 6. In the graph, the red line indicates the median value of the norm of interaction forces for each time step, the black bar indicates the total range of the data, and the blue box indicates the data range between 25th percentile and 75th percentile.

IV. Discussion

The local minimum norms of the interaction forces were observed at the 6 ms and 40 ms. The obtained interaction forces in the cases of 6 ms and 40 ms time step were less noisy than in the case of 2 ms times step. The results are related to the low pass filtering effect of slow sampling. If the sampling rate is not too low compared to the velocity of the intended motion, the slow sampling has advantage of low pass filtering effect without phase delay. In addition, there are multiple redundant sensor readings in the higher level loop, because the higher level update time step(t_u) is larger than the sampling time (t_s). For example, if the higher level update time and sampling time are 40 ms and 2 ms, respectively, 20 values of force sensor (=40 ms/2 ms) are available per one update time of higher level loop. These redundant readings can be used to estimate the pure intention by signal processing such as moving average and tremor cancelation method. In order to compare the results, as shown in Fig. 6, multiple comparison test based on the analysis of variance (ANOVA) was carried out. There are no significant differences in the norms of interaction force in the ranges between 2 ms and 80 ms time step. This is

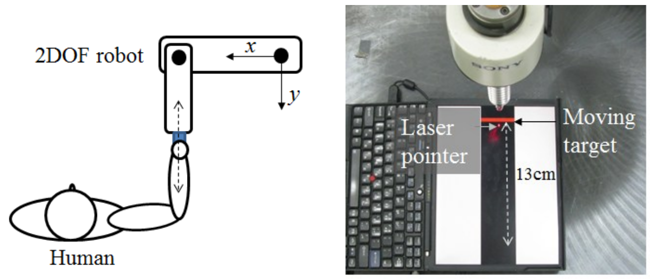

Fig. 3. Control variables: the direction of the movement (left); the velocity of the movement. Subjects are asked to follow the moving target tracking the laser pointer (right).

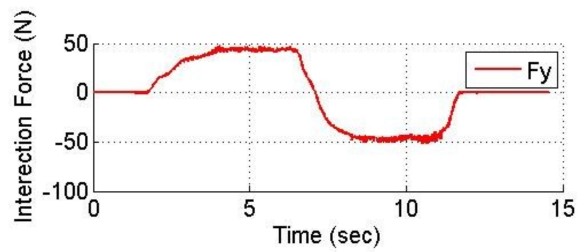

Fig. 4. Interaction force during the pull-and-push movement without control

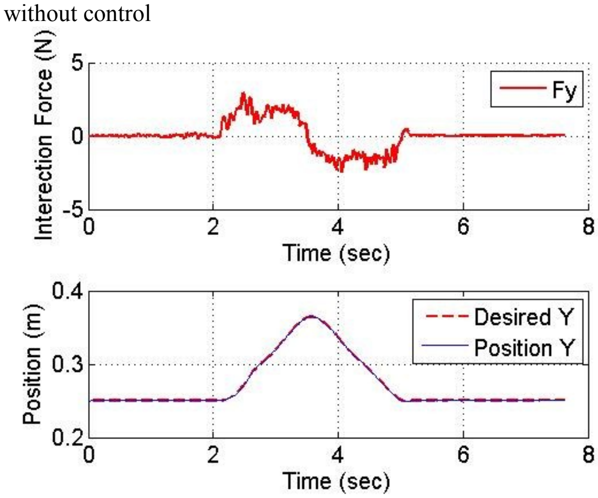

Fig. 5. Interaction force during the pull-and-push movement with control using 60 ms time step (top), the desired position of the hand along they direction, and real position of it (bottom)

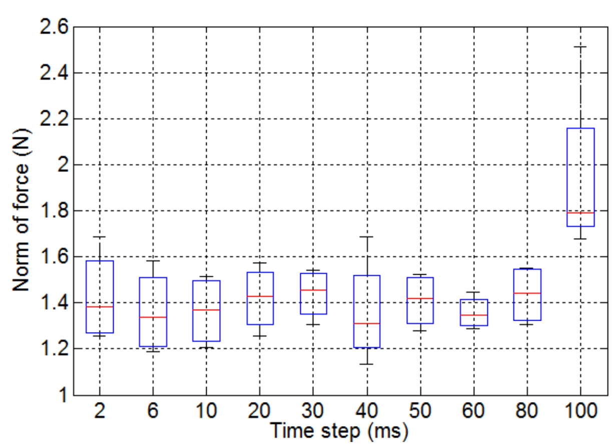

Fig. 6. Multiple comparison test based on ANOVA. There are no significant differences in the range of 2 ms~80 ms time step .

interpreted as the result is related to the force sensitivity. Since the bandwidth of the mechanoreceptors in skin, such as merkel disks and ruffini corpuscles, is about 10 Hz [19], the human cannot notice the fast force changes under near 100 ms. The results show that slow sampling time under 100 ms can be used to cooperative control in pHRI. We expect that the minimum norm of interaction force is obviously observed in certain time step between 2 ms and 100 ms. Although the local minimum points are observed at 6 ms and 40 ms time step, the multiple comparison tests show that they are not significantly different compared to the interaction forces in the range between 2 ms and 80 ms time step. However, the number of subjects is only two and the number of trials also only 10 times, the local minimum points should be investigated more in detail.

V. CONCLUSION

This paper proposes the cooperative control strategy with two time steps to investigate the effects of the sampling time sizes in pHRI. Because the strategy has two time steps, multiple designs of experiments could be possible. The 2DOF planar robot as a measurement device of force and position in pHRI was used to find the suitable time step. From the Fig. 6, there were no noticeable differences in the ranges under 80 ms time step, and the interaction force in the case of the 100 ms is significantly larger than the interaction forces under 80 ms time step. It makes sense with the widely accepted fact that the system becomes unstable with the increase of the sampling time or the time delay [20].

The results indicate that the boundary of the sampling time sizes in pHRI. The back-and-force tasks were successfully performed with small interaction force using slow sampling time under near 100 ms which is in accordance with the bandwidth of the mechanoreceptor of the human, 10 Hz. The vibration phenomenon was observed in the cases of the 2 ms and 100 ms. We finally chose 60 ms step which the smallest variance of the interaction force was observed, and implemented to 2DOF robot. As mentioned in discussion, more experiments with various subjects are necessary to confirm the results based on statistical validation. After the validation of the best update time step, it can be used to pHRI applications such as assistive robotics systems.

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