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Balancing the sticks with fluctuation and delay: Human vs Machine

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Abstract— **We compared the similarities and differences in stick balancing for the human fingertip and that by a servo–controlled machine. The motion of the stick in both cases exhibited a swinging or hunting behavior, which appears to be related to feedback delay. However, human stick balancing appears also to be affected by psychological factors, such as attention, which are not present in machine control systems. We discuss how machine control systems compare with human stick balancing.**

I. Introduction

A lot of attention has been given to balancing sticks and inverted pendulums in control engineering [1]. When someone tries to balance a stick on their fingertip or palm, many factors are involved. The physiological delay of a human is on the order of 0.1 second [2][3] and longer compared to machines. Humans also use predictions on the motion of sticks, which are not as reliable as machines. We focused our attention on the simple task of stick balancing. We found that even for this simple task, there appears to be notable similarities and differences between humans and machine controls. We have conducted stick balancing task experiments on both humans and machines, and, though both experiments are ongoing, we are reporting our results on some of the similarities and differences between them.

II. Human stick balancing

Human stick balancing involves many factors. Recent experiments show that much of the corrective motion of the stick on the fingertips is faster than the human physiological feedback delay. This indicates that there are more processes involved in this task than the feedback controls. Recently, an interesting observation was made. When a person rhythmically moved an object in one hand, balancing a stick in his or her other hand improved (Fig. 1)[4][5]. This was observed particularly with people who had intermediate balancing skills. We measured the time that they could keep the sticks balanced, and compared it with normal non-movement situations. Some examples are shown in Figure 2.

Following this line, other experiments were performed in which a person rhythmically moved his or her leg instead. These produced similar results. One hypothesis we formed from this was that an appropriate level of added fluctuating or rhythmic motion improved the balancing control with delayed feedback [6].

Fig. 1. Picture of subject balancing stick in one hand while moving object in other.

We posed another question concerning the nature of this fluctuation in improving the balancing control. Is it limited to physical noise? To address this question, other experiments were performed in which a person was asked to just imagine moving his or her leg during the stick balancing task. The results showed similar effects as those indicated in Figure 3 [7]. This implies that fluctuations in the level of intentions or thoughts may affect effectively during the stick balancing. Another hypothesis is that these fluctuations appropriately disrupt the feedback control loop. Relying too much on feedback control with human delay times could lead to less control during stick balancing tasks, and an appropriate level of intention diversion improves the control. Even though we need to perform more experiments under a variety of conditions, from these results we believe that human control intricately involves various factors.

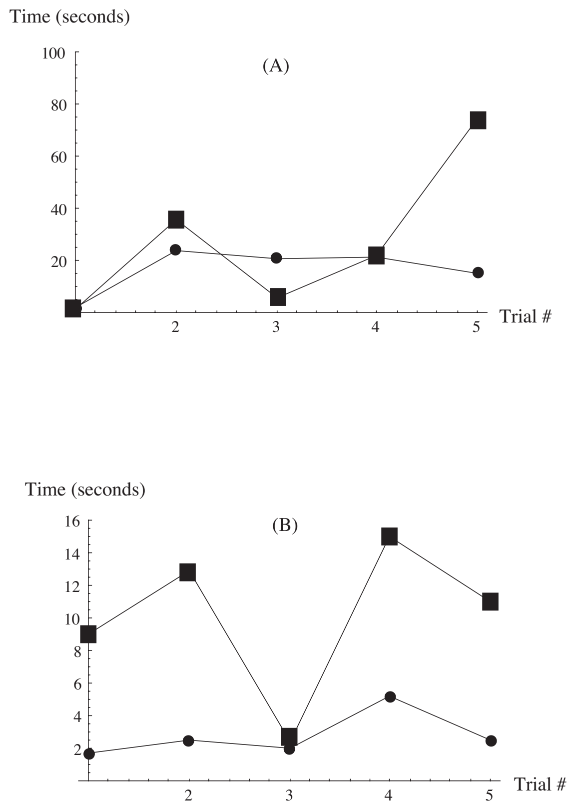

Fig. 2. (A) Example of improvement on balancing tasks with (squares) and without (dots) moving an object. The subject was given five trials without previous practice. By the fifth trial, the improvement was significant. (B) Another subject practiced for a few hours. Here, again object movement improvement was evident.

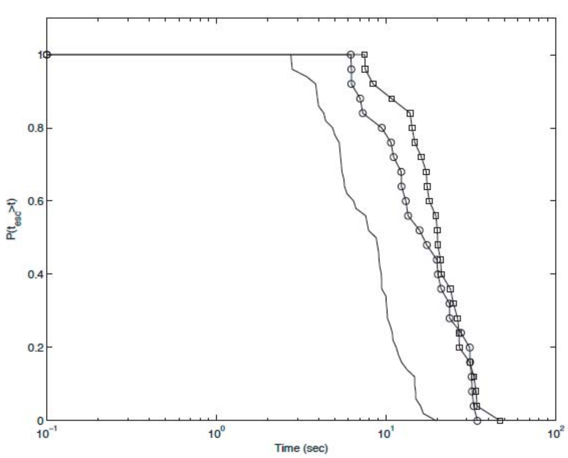

Fig. 3. Example of result from human stick balancing experiments. It shows the accumulative probabilities for the time duration in which subjects can balance the stick before it falls. The results from moving legs (circle), just imagining moving their legs (squre), and normal balancing (line) are compared. This graph shows the first two cases improve the balancing time durations.

III. Simulation of stick balancing with human hand using inverted pendulum

When people try to balance a stick on their hand, they fully exploit the three degrees of freedom, but in mechanical device simulations it is more convenient to limit the number of degrees of freedom. For that reason, we constructed a well–known inverted pendulum, which has only one degree of freedom. Moreover, the pendulum for our experiment was a simple straight stick with no articulation, which made the control system much simpler. Figure 4 shows a block diagram of the system and Fig. 5 an overview of it.

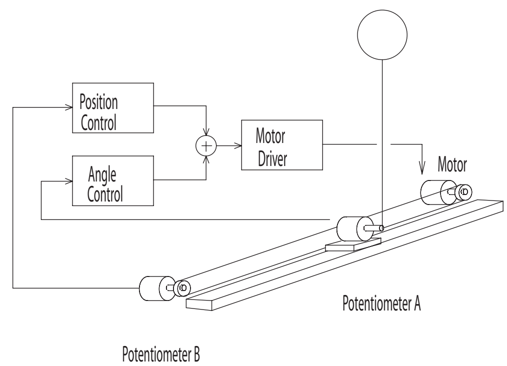

Fig. 4. Block diagram of inverted pendulum control system.

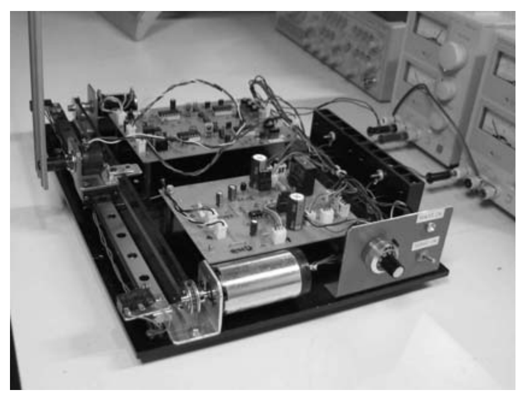

Fig. 5. Photograph of inverted pendulum control system.

The effective length of the rail on which the inverted pendulum can move is 280 mm and the length of the pendulum is 390 mm. A potentiometer placed at the fulcrum of the pendulum detects the angle of the pendulum from the vertical position. A DC servo motor drives the slider on the rail using a timing belt, and the position of the rail is detected by a multi-rotational potentiometer, which is unnecessary if we control only the pendulum. However, at first, we intended to control the pendulum and its standing position simultaneously, and that is why the rail is relatively short. Two sets of control electronics are also provided for measuring the pendulum angle and base position. The two error outputs for the angle and base position were eventually added to produce the input signal for the motor driver. All of the electronics are analog circuits using operational amplifiers. The DC motor is driven by a power amplifier, which is quite similar to an (analog) audio amplifier, and we noticed it had an inactive area of the DC motor around zero volt output, but this was not critical. The timing belt compliance is very small and will not introduce unwanted poles within the bandwidth of the servomechanism.

A. Automatic system control

We started our experiment by controlling the slider position, which is detected by the multi-rotational potentiometer. The position is determined by adjusting the DC bias of the control circuitry (This DC bias gives the operating position.). For the slider position control, the overall control is identical to that of the old DC–motor–operated plotters. Having established the position parameters of the control circuitry, we then designed the pendulum control. Both were designed by a conventional PID control. A block diagram of the system is shown in Fig. 6, which also shows that both control loops have the second order transfer function.

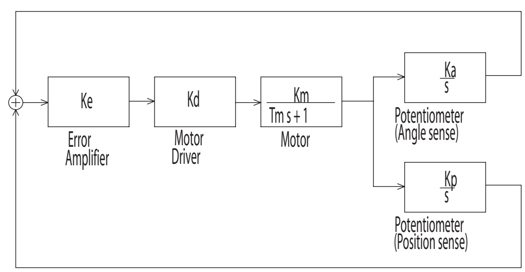

Fig. 6. Block diagram of PID control in our system.

Strict parameter designs always involve tedious steps, such as measuring the physical properties (mass, inertia, and torque characteristics of the motor) and calculating the transfer functions to meet the specifications. This time, however, we experimentally determined the parameters of the proportional (P) loop and then gradually added the Integrational (I) loop. Feedback loops consisting of only P loops create the first order transfer functions, which are always stable. (This corresponds to the characteristics of the open loop and the voltage follower of the operational amplifier.) By adding the I component to the P loop, we found that the system had the well-known characteristics of a second-order system, and it is up to the designer to make the response asymptotically stable or put it into a hunting state.

B. System operation

The I loop is absolutely necessary to balance the inverted pendulum, because the average error to the right and left is zero only at the balanced inverted angle (or vertical downward direction for non-inverted conventional pendulums). That is, when the control works to make the integration error zero, the inverted stick balances. (The differential (D) loop, in theory, provides phase compensation by using a transfer function, but in practice, it can be regarded as speeding up the parts of the operation that were slowed down by the I loop.) Our initial idea for controlling the position of the slider was to add an error signal bit by bit to the already stably inverted pendulum – basically, to deceive the pendulum while it was stable. We can then shift the slider position as we wish. However, the position control (negative feedback) loop of the slider functions like a positive feedback loop to invert the pendulum and vice versa. This means that when we increase the slider position error so that the position shift is effective enough, the inverted pendulum loses equilibrium and starts hunting. Therefore, we eventually had to cut off the control loop for the position of the slider and operate only the control loop for the inverted balancing. Thus, the inverted position was not determined, and the 280 mm rail turned out to be insufficient. A much longer rail or a rotational-arm style would be more suitable. On the basis of these experimental results, we believe that humans cannot asymptotically control the position while balancing a stick if the hand movement is restricted to the horizontal plane.

C. Stability with signal delay

When signal delay is introduced into asymptotically stable control systems, they usually destabilize because they are rarely intentionally designed to include signal delay. However, when balancing a stick by hand and in a simulation with an inverted pendulum, we need more than asymptotic stability. The drum cylinder motor control of a video cassette recorder is an example of a common asymptotic control. It rotates with constant speed and locks onto certain reference signals as stably as possible. We believe position control and balance are contradictory (at least under some restrictions, as previously stated) in human stick balancing, and we have not yet observed asymptotically stable stick balancing done by a human. What we observed instead was a very unstable, yet different from falling, human stick balancing. From an engineering point of view, if a master stick balancer balances his stick asymptotically in one position, it will be very interesting – although, to the general audience, rather boring. Therefore, one's range of arm movement when balancing a stick should be wider than that necessary to achieve asymptotic stability. The stability achieved when the stick does not fall is an example of Lyapunov stability [8]. This is the reason we intentionally added signal delay to our experimental system, and then a new problem arises concerning the suppression of hunting, even temporarily, to prevent the stick from falling off by creating Lyapunov stability.

D. Delay controller

To achieve signal delay, we designed the equipment shown in Fig. 7. It is a very simple principle. An input signal is AD converted and then written to a static RAM. The contents of the RAM are read out after a specific amount of time and are then DA converted to produce an output signal. The current sampling period is 1 ms, the maximum signal delay

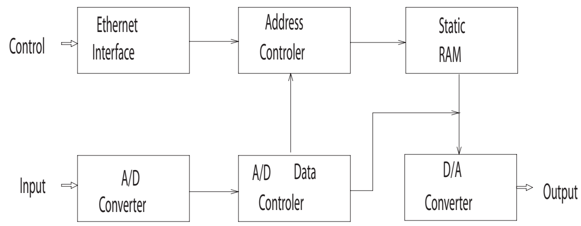

Fig. 7. Block diagram of delay controller.

is approximately 4 s, and the granularity of the control is 1 ms. The delay value is controlled by an outside PC via an Ethernet. Since there can be several circuit points to inject delay in control systems, which might be controlled in parallel, we produced four identical delay control circuits. (However, we are currently only using one.) A photograph of the delay equipment is shown in Fig. 8.

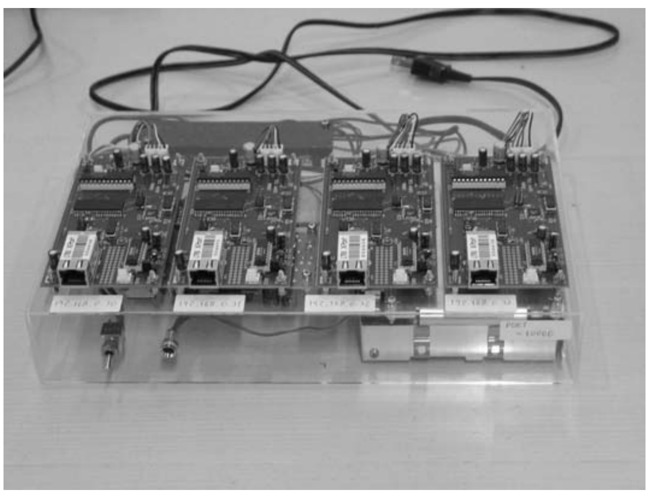

Fig. 8. Photograph of delay controller.

E. Effects of delay

We measured the transfer function of the inverted pendulum both with and without delay. We used a sinusoidal input signal to measure it and compared it to the sinusoidal output error signal. All measurements were performed using a general signal generator and a PC. Figure 9 shows the transfer gain and phase shift functions. The delay was set at 0, 1, 5, and 10 msec. When there was no delay we observed peaks of about 3 db around 9.5 Hz. When delay was introduced into the system, we observed an increase in the peak intensity to about 10 db. The peak frequency was also shifted lower to 5.5 Hz, and we think this shift was caused by the limit of the system slew rate, because the magnitude of the movement increased as the system became less stable. However, with this level of delay we do not observe hunting.

Then we set the input signal frequency to 2 Hz, and compared the delays at 5 msec and 15 msec. The 5–msec delay

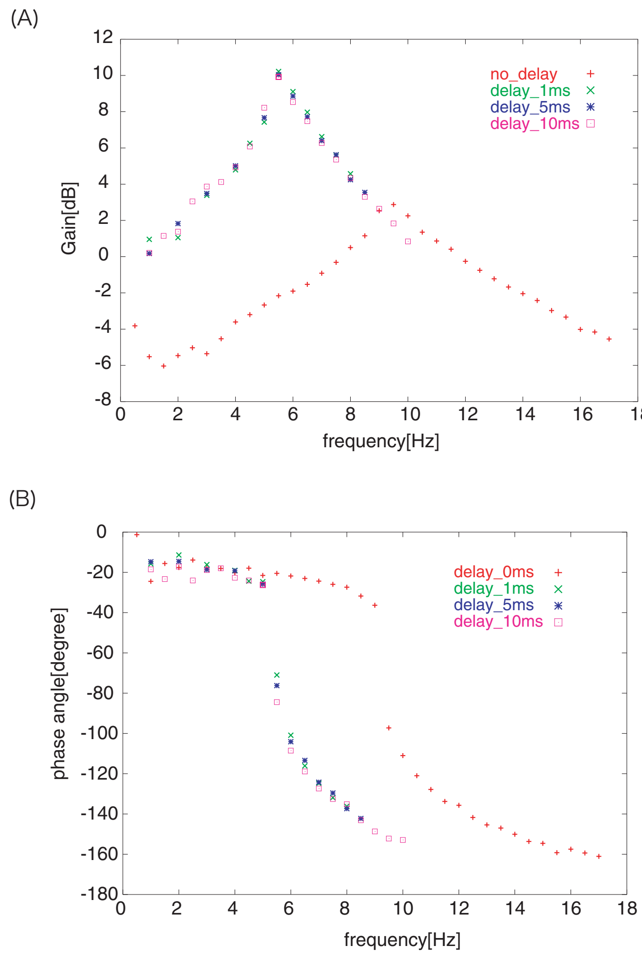

Fig. 9. Transfer gain (A) and phase shift (B) diagrams as we changed value of delay in system.

does not show any hunting, but the 15–msec delay did. We noted that when hunting takes place the response frequency differed from the input frequency (Fig. 10).

As we increase the input frequency using the 15–msec delay, we again saw the locking of the response frequency to the input between around 4 to 10 Hz. This was probably caused by delay signals that induced a phase shift and hunting with the input frequency. A similar phenomena can be observed with a Wien bridge oscillation circuit.

F. Discussion

If we regard the system is stable as long as the pendulum does not fall, suppressing hunting even temporarily could be effective. That is, if hunting is temporarily suppressed, the pendulum will not fall, and the system will keep going. One idea is to apply an inverted signal of the hunting error signal (we already know the hunting frequency) to the system when hunting starts. In this scheme, we have to detect the beginning of the hunting, which means that we must allow hunting to begin and then suppress it temporarily. We believe the

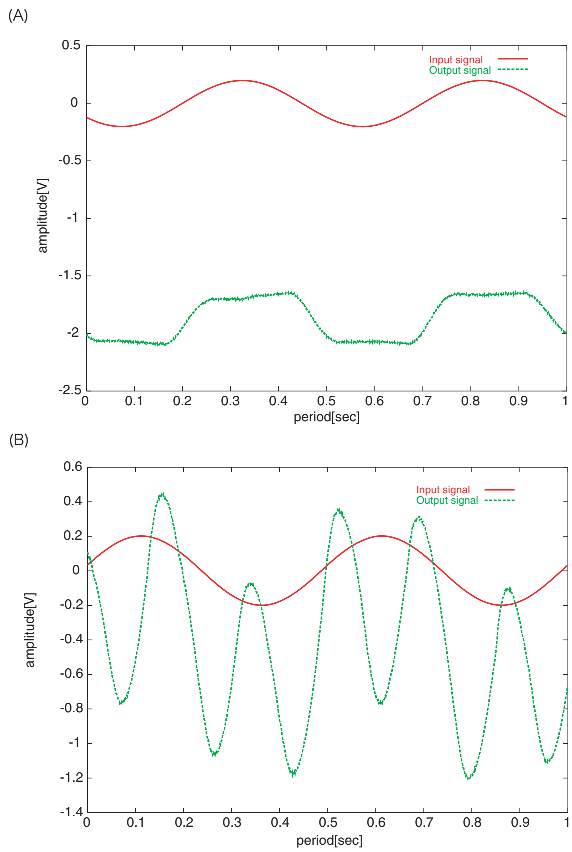

Fig. 10. Plotted response frequency when input signal is 2 Hz. The delay value is (A) 5 msec and (B) 15 msec.

repetition of a "hunting –suppress hunting" sequence takes place. In this way, the system can keep the stick from falling. This is a rather different view of the controls from traditional control schemes, where the asymptotic stability is typically the goal. However, this may be one of the controls humans perform during stick balancing.

Also, human controls may involve more factors such as psychological ones, as we have observed. With machine controls, this is analogous to the internal parametric tuning for better balancing. We have not pursued this direction of machine control with our system. In addition, we are currently investigating whether an added fluctuation or noise could indeed improve balancing even with machine controls.

Overall, we have found certain similarities in stick balancing, such as hunting motion, between humans and machines. Yet, certain factors, such as psychological fluctuations, require further investigation using human experiments as well as pursuing the question of how to implement such factors into a machine. Stick balancing is an old topic, yet continues to provide us with challenges.

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