Digital Position Control for Analog Servos

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Abstract— **RC-servos are widely used to build robots with many degrees of freedom, because they are small, inexpensive, and easy to interface. Their main advantage, though, is their good weight-to-torque ratio. Many robots in the RoboCup Humanoid League, for example, almost entirely consist of servos. RC-servos come in two flavors: analog and digital. In analog servos, the internal controller is synchronized to the pulse train that encodes the target position. A typical problem of analog servos is that they suffer from large position tracking errors and variations of the zero-position which are caused by changes in temperature and/or supply voltage. To overcome these problems, digital servos have been introduced in the last years. Digital servos are, however, about twice as expensive as analog servos. Furthermore, all large servos are still analog.**

We constructed the legs of a 120cm humanoid robot from large analog servos. To improve position control, we modified the servos by replacing in the internal circuit the potentiometer with two equivalent resistors. The potentiometer is now interfaced to a microcontroller that measures position, implements digital position control, and sends motion commands to the analog servo controller. This approach makes it possible to use more advanced control techniques, compared to the original controller. For example, long-term position errors can be avoided by integrating the short-term error. Similar to other intelligent actuators, the parameters of the controller can be changed on a fast time scale, e.g. depending on the gait phase. Furthermore, the digital actuator is able to generate feedback for higher control levels. As the microcontroller is shared between multiple servos and was already in place prior to the modification, the additional hardware needed is negligible.

We evaluate the proposed approach using systematic test signals. The results indicate that position control is more precise, more flexible, and more stable than before.

I. INTRODUCTION

When building robots with many degrees of freedom (DOF), the choice of the actuators is one of the most important design decisions. Several constraints must be observed when selecting actuators. For example, the actuators must be strong enough and fast enough to drive the load at the desired speeds. They should be easy to control. The source of energy must be available onboard the robot. They should be compact, light weight, and robust. Last, but not least, the cost of the actuators is also an important factor.

Similar constraints must be met in model airplanes and cars. For these applications, RC-servos have been developed. They consist of a DC-motor, a matched gear, a position sensor, and an electronic controller. RC-servos are small, inexpensive, and easy to interface. The target position is set using a pulse train on a single input line. Because they must fly, many RC-servos have an exceptional weight-to-torque ratio. For these reasons, servos are very popular in many of the RoboCup leagues [1]. Most of the robots that compete in the Humanoid League, for example, almost entirely consist of servos [2], [3].

RC-servos come in two flavors: analog and digital. In analog servos, the internal controller is synchronized to the 50Hz pulse train that encodes the target position. A typical problem of analog servos is that they suffer from large position tracking errors and variations of the zero-position which are caused by changes in temperature and/or supply voltage. To overcome these problems, several manufacturers introduced digital servos in the last years. They include a microcontroller that runs position control on a faster time scale, e.g. at 300Hz. This makes control more precise. Digital servos are, however, about twice as expensive as analog servos. Furthermore, all large servos are still analog. The largest digital servo on the market is the Hitec HS-5745MG, which weighs 161g and has a rated torque of 18kg·cm, insufficient to drive the legs of larger humanoid robots.

For this reason, we constructed the legs of our 120cm humanoid robot Fritz from large analog servos [4]. The Tonegawa PS-050 servos [5] have a weight of 290g and a torque of 110kg·cm when supplied with 12V power. 5 servos are used per leg.

This paper describes a method to wrap digital position control around such analog servos. We modified the servos by replacing in the internal circuit the potentiometer with two equivalent resistors. The potentiometer is now interfaced to a microcontroller that measures position, implements digital position control, and sends motion commands to the analog servo controller.

This approach makes it possible to use more advanced control techniques, compared to the original controller. For example, long-term position errors can be avoided by integrating the short-term error. Similar to other intelligent actuators [6], the parameters of the controller can be changed on a fast time scale, e.g. depending on the gait phase. Furthermore, the digital actuator is able to generate feedback for higher control levels.

The remainder of this paper is organized as follows. The next section describes the working principle of analog servos. In Section III, we detail the modifications made to an analog servo in order to implement digital position control. The modified servo is compared to an unmodified servo using systematic test signals. The results are presented in Section IV. The paper concludes with a discussion of the results.

Proceedings of the Workshop on Humanoid Soccer Robots
of the 2006 IEEE-RAS International Conference on Humanoid Robots
Genoa, Italy, December 4, 2006
pp. 56-61
ISBN: 88-900426-2-1

II. ANALOG SERVOS

A. Working Principle

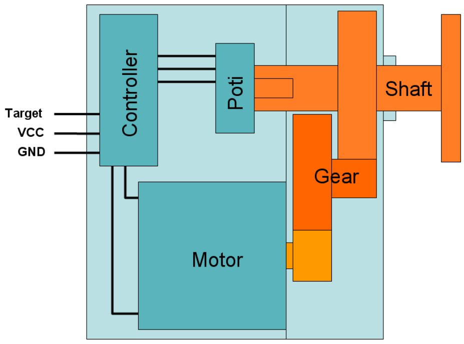
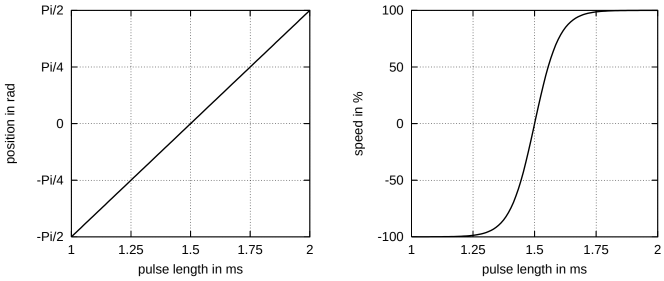


Fig. 1. Working principle of analog RC-servos. See text for details.



(a) (b)

Fig. 2. Effect of the control signal: (a) position control in unmodified servos; (b) speed control in modified servos.

The working principle of analog servos is illustrated in Fig. 1. Three wires supply ground, the operating voltage, and a position target. This target is encoded as train of variable-length pulses with an inter-pulse distance of typically 20ms. The pulse length represents the target position as follows: 1ms pulse length commands the servo to the leftmost position, 1.5ms correspond to the middle position, and 2ms to the rightmost position. The linear pulse-length-to-position curve is illustrated in Fig. 2(a).

The internal servo controller compares this position target to the shaft position, which is measured using a potentiometer. Depending on the position error, the motor is driven into the direction that minimizes the error. Driving strength depends on the size of the error.

B. Modified Servos

The range-of-motion of RC-servos is limited to typically ±90°. In order to drive the servo shaft with continuous rotation, a simple modification is commonly used. The potentiometer is replaced with two resistors of equal resistance that add up to the total resistance of the potentiometer.

From the perspective of the internal controller, the servo shaft now seems to be always in the middle position. This changes the meaning of the pulse train on the control line. 1.5ms pulses yield zero position error. Hence, the motor is not driven and the servo does not move. 1ms pulses yield the maximal negative position error and the motor is driven fully to the left. Symmetrically, 2ms pulses make the motor turn right with maximal speed. The resulting pulse-length-to-speed curve has a sigmoidal shape, as illustrated in Fig. 2(b).

Such modified servos have been used in many wheeled robots, like the Palm Pilot Robot Kit, a three-wheeled omnidirectional robot developed at CMU [7], and Hancor, a two-wheeled robot developed at FIU [8].

III. DIGITAL POSITION CONTROL

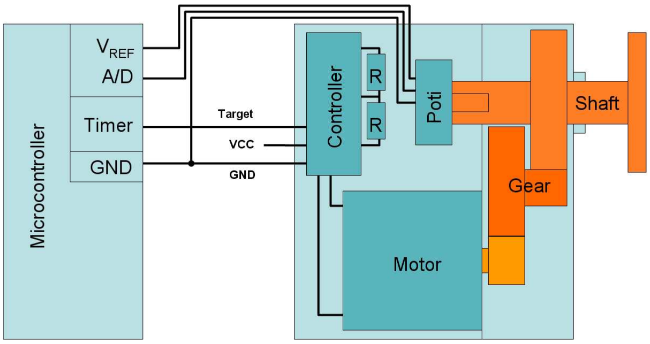


Fig. 3. Digital position control wrapped around analog servo.

We built on the modification described above in order to implement digital position control, as illustrated in Fig. 3. The mechanical connection between servo shaft and the potentiometer is left unchanged, but the potentiometer is electrically disconnected from the internal servo controller. It is interfaced to the A/D converter of a microcontroller. The microcontroller now can read the potentiometer voltage, which corresponds to the shaft position. It compares the actual position with the target position and issues motion commands, encoded as pulse train, to the servo. The pulses are generated with 16Bit accuracy by the timer module of the microcontroller.

This digital position control is much more flexible than the internal servo controller. Because the controller is now described in software, it is easy to implement more complex control strategies. For example, a full PID-controller [9] can be realized by observing not only the current position error $e(t)$, but its integral and derivative as well:

$$\text{output} = K_c \cdot \left[e(t) + \frac{1}{I} \int e(t)dt + D\frac{de(t)}{dt} \right]. \qquad (1)$$

K_c denotes the controller gain. While the integrator part I avoids long-term position error, the differentiator part D can be used to damp overshoots. The parameters of a PID controller can be tuned, e.g., using the method proposed by Ziegler and Nichols [10].

In contrast to hardware controllers, it is easy to change the parameters of a software controller. This can even be done on a fast time scale, yielding an intelligent actuator that can be configured not only by the target position, but also by control gain, maximal speed, etc. This on-the-fly configuration makes it possible to adapt the control to changing load conditions, which are typical for bipedal walking.

Finally, the microcontroller can easily provide feedback about the current state of its controller to higher control layers. Possible quantities of interest include the current position, the position error, the integrated error, and the issued motion command.

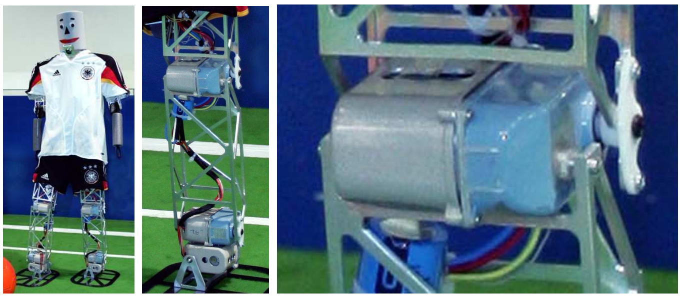


Fig. 4. Humanoid robot Fritz, its left leg, and its left knee.

Our humanoid robot Fritz, shown in Fig. 4, has one microcontroller in each leg that is connected via CAN bus and RS232 to a main PC. The PC sends regularly target positions for the individual joints to the microcontroller. The microcontroller reports back about its state. The PC is used to keep track of both targets and state variables.

Prior to the modification, each leg-microcontroller generated pulses encoding the target positions for its 5 analog leg-servos. Now, it implements for each servo a PID controller, as described above. This has the advantage that only two resistors per servo are needed for the modification.

Because the pulses for the individual servos are interleaved (one pulse every 2.5ms), the implementation of up to eight controllers does not need more computing power than needed for each individual controller. This interleaving has also the advantage that the peak current consumptions of the servos do not occur simultaneously, but are distributed in time.

IV. RESULTS

In order to compare the behavior of the implemented digital controller to the behavior of the original analog controller, we made the robot sit on the edge of a table. Both legs were adjusted to be parallel. The thigh of each leg was fixed in horizontal position at the tabletop. The shanks of the legs hung in a vertical position whenever the servos were not powered. For the left knee joint, we implemented digital position control, whereas the right knee was driven by an unmodified analog servo. Because each lower leg weights approx. 0.7kg and its center of mass is approx. 27cm away from the knee axis, holding the lower legs in horizontal position induces a torque of approx. 18.9kg·cm.

A. Changing Load

In the first test, we periodically added a weight of 1.73kg at a distance of 24.2cm from the knee axis while the lower legs were in horizontal position. This increased the torque by 41.9kg·cm to 60.7kg·cm.

Fig. 5 shows for the digital servo the knee position, the integrator, and the controller output over time. One can observe that the integrator accumulates the position errors, which are caused by the additional load. Because the integrator increases the controller output, the position error is corrected. For comparison, Fig. 6 shows the position of the analog knee servo under the same conditions. It is clear that the original controller fails to correct the position error, because it does not include an integrator. It can also be observed that the position of the analog servo drifts over time towards positive angles. This is caused by the temperature increase in the servo.

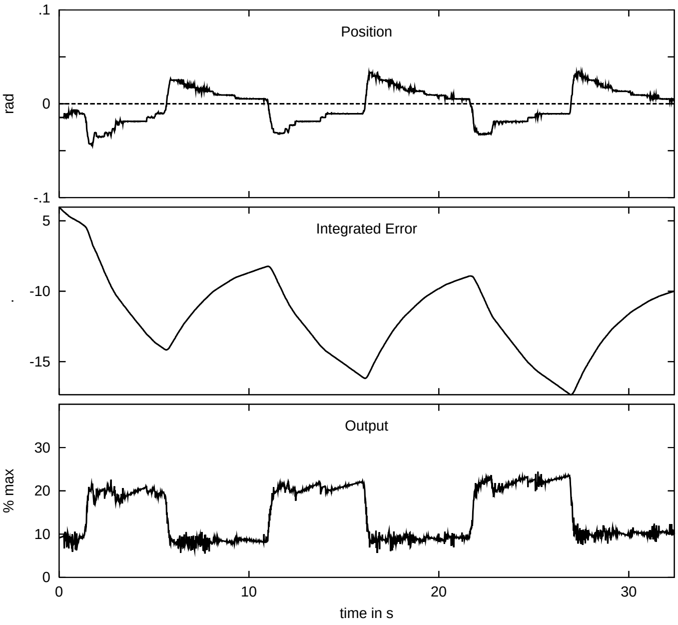


Fig. 5. Digital servo: Changing load with zero target. The integrator corrects for the position error.

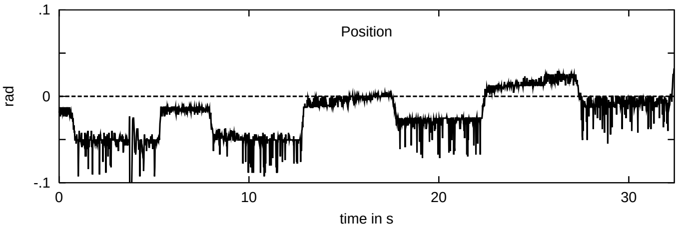


Fig. 6. Analog servo: Changing load with zero target. The controller fails to correct the position error.

B. Temperature Drift

To illustrate this effect more clearly, we moved both servos simultaneously on sinusoidal trajectories. The frequency of the oscillation was 1Hz and the amplitude was 0.1rad. We started with a servo temperature of 20°C (room temperature). Due to the movement, the servo temperature increased to approx. 60°C. Fig. 7 shows that the integrator of the digital controller is able to correct for the drift of the zero-speed pulse length. In contrast, the analog servo, shown in Fig. 8 drifts significantly towards positive knee angles.

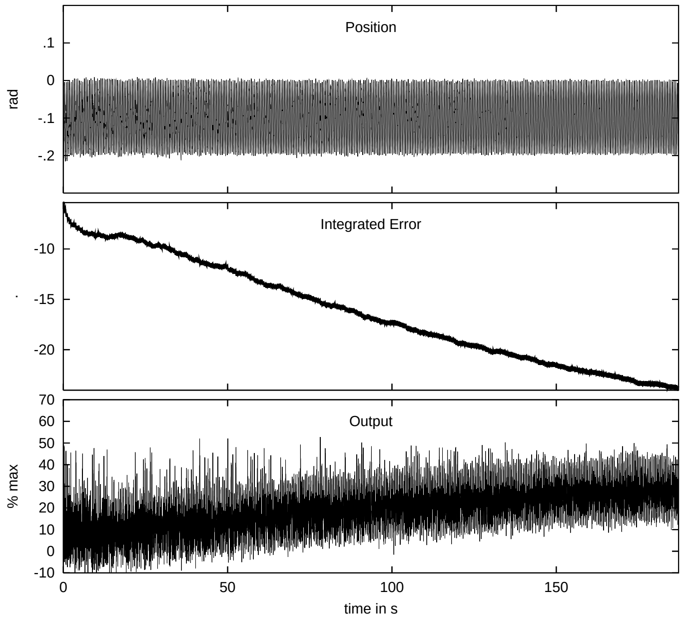


Fig. 7. Digital servo: Temperature change. The integrator corrects for the drift in the zero-speed pulse length.

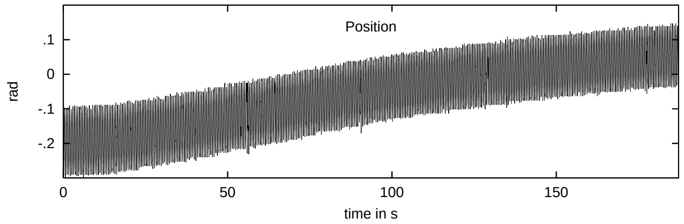


Fig. 8. Analog servo: Temperature change. The zero-position drifts.

C. Slow Startup

A final experiment demonstrates the change of control parameters on a fast time scale. Because in the moment of switching on position control, the actual and the target positions differ significantly, the analog servo moves to the target position with high speed. This causes high mechanical stress and also leads to overshoots. Fig. 9 shows this behavior for a zero target position. In order to avoid these problems, we implemented a slowly increasing limit for the controller output. As shown in Fig. 10, after starting position control, the digital controller slowly moves the joint towards the target.

V. CONCLUSIONS

This paper described a method to wrap digital position control around analog RC-servos. We implemented the proposed approach for the large leg-servos of a 120cm humanoid robot. As the microcontroller, which executes digital position control, is shared between multiple servos and was already in place prior to the modification, the additional hardware needed was negligible.

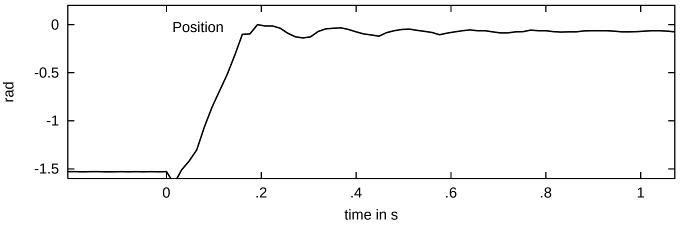


Fig. 9. Analog servo: Starting position control leads to high mechanical stress and overshoots.

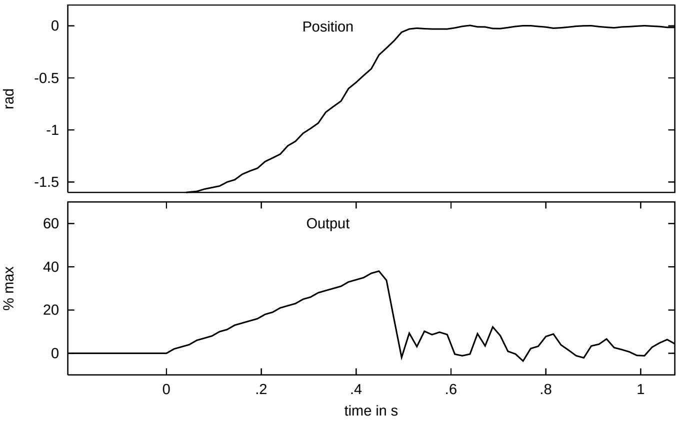


Fig. 10. Digital servo: The slowly increasing output limit avoids quick movements and overshoots at startup.

Digital control made it possible to use more advanced control techniques, compared to the original controller. For example, long-term position errors were avoided by integrating the short-term error. This was particularly useful to correct for drifts in the zero-position of the analog servo, which are caused by changes in temperature.

The interface to the actuator is more flexible now. For example, the parameters of the controller can be changed on a fast time scale. We used this to implement slow startup of the position control in order to avoid mechanical stress and overshoots. Changing control parameters can also be useful when the load conditions change predictably, as in bipedal walking.

The third advantage of the proposed digital actuator is that the microcontroller is able to generate feedback about the state of its joint controllers for higher control levels. This feedback can also be used to keep track of the state variables.

The combined effect of these improvements made it easier to implement walking for Fritz, using the approach described in [11]. Fig. 11 shows some frames extracted from a video of the walking robot. Please note that Fritz is now equipped with a 16DOF communication head with movable cameras. Its step frequency is approximately 1.4Hz and it walks with a speed of about 10cm/s. The video can be downloaded from http://www.NimbRo.net.

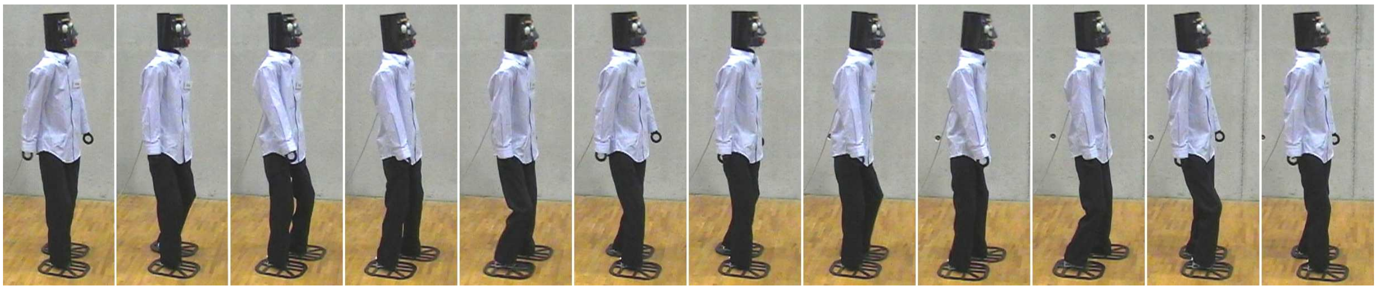


Fig. 11. Image sequence extracted from a video showing the walking robot Fritz with communication head.

ACKNOWLEDGEMENTS

Funding for the project is provided by Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) under grant BE 2556/2-1 and by Albert-Ludwigs-Universität Freiburg.

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