Reducing the Impact of Low Quality and Resolution Speed Sensor on Digital Speed Servo Control System Utilizing a Speed Observer

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Article information	Abstract
Key words *Rotational quadrature encoder- decoder sensor; rotational speed servo control system; real time control system.* *Received 12 06 2025, Accepted 28 06 2025, Available online 01 07 2025*	In this paper, the impact of the low resolution and low quality speed sensor on the performance of a speed feedback servo control system is studied, in terms of the error between the set point and the actual output. Therefore, a low quality speed sensor is designed based on the computation of the speed signal by the derivation of the low resolution incremental quadrature encoder-decoder position signal, the sensor is then implemented in a speed feedback servo control system and compared to a system with an ideal sensor, next, the sensor low quality speed signal is enhanced by designing and implementing a speed observer to estimate the speed signal based on speed measurements first, second, the speed observer is extended to be based on position measurements, where the second observer outperforms the first one. Moreover, the control algorithms based on the developed second observer are also applied on a real hardware experiment successfully in real time control.

I. Introduction

It is very common practice in control engineering, the tuning phase of the controller parameters starts after the installation of the feedback control system hardware and its initial operational tests. Usually the goal of controller final tuning is to obtain the best possible performance from the installed hardware system. One of the main performance demands is the minimization of the error between the set point and the actual system output, but this is always limited by the quality and resolution of the installed sensor, for example, if an incremental encoder sensor has a resolution of 360 pulses per revolution (ppr), which is one degree per increment or a step (dps), is used in a position servo control system, the sensor only detects increments of one degree steps, and therefore, the minimum actual error of the feedback loop is limited to one degree range, even when the measured error is zero, if the target is to have smaller error say about 0.1 degree, then another sensor with a higher resolution of 3600 ppr or 0.1 dps is needed to achieve this tolerance target [1]. Note that the

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measured error is the difference between the set point and the measured output from the sensor, while the actual error is the difference between the set point and the actual (true, real) output. The actual output is measured with errors depending on the quality and resolution of the sensor; regrettably, the actual output can only be known exactly in a digital simulation environment. Hence, to obtain a minimum actual error, the sensor must have a maximum resolution with a high quality signal, this is always encountered with an increase of effort, cost and complexity of the feedback control system, which is the maximum (effort, cost, complexity, etc.) boundary limit.

In practice therefore, the question always arises, how to increase the performance of a feedback control system, be by decreasing the steady state actual error between the set point and the actual output, without replacing any of the already installed hardware parts in general and the installed sensor in particular. In other words, for any resolution of the installed sensor used to close the loop of a feedback control system, the problem is how to increase the performance by reducing the steady state actual error without replacing the installed sensor. This means, achieving it only by changing the software and without changing the hardware. One common solution to this practical design problem is to use a state observer, which it can be used to enhance the measured output from the sensor when the observer has a relatively good internal plant model [2, 3, 4], which allows to be designed with low gain values. The impact of low resolution sensors with low quality signals on the feedback control system performance is one of the mainstream subjects of research studies for sensors in general [5, 6] and quadratic incremental encoders in particular [7, 8, 9, 10, 11].

Therefore, in the next section, a low resolution and low quality speed sensor presented as a rotational speed computer is designed to compute the rotational speed from the position signal of a low resolution rotational quadrature incremental encoder-decoder sensor [1]. In section III, the speed sensor is implemented in rotational speed feedback servo control system and compared to a feedback system with an ideal sensor. Moreover, the low quality signal of the designed speed sensor is enhanced by designing and implementing a speed observer to estimate the speed signal based on speed measurements. Second, the speed observer is extended to be based on position measurements. Furthermore, in section IV, the developed observer control algorithms are applied in real time to control a real hardware system. Finally, some conclusions are given in section V, and the references are presented at the end.

II. ROTATIONAL SPEED COMPUTER

It is obvious that the derivation of the speed directly from the decoded incremental position signal is not consistent due to the position signal has sudden increments in form of steps; therefore, it is mathematically not a continuous function. In other words, the output of the incremental decoder is similar a zero-order-hold sampled position signal with a variable sampling rate which is directly related to the speed, that is, the derivative of the position. Nevertheless, the derivative can be cautiously computed using a difference computer divided by the sampling time, which is alternatively called as a discrete derivative computer. Now assume that a continuous position signal is sampled two times successively and then a discrete derivative is computed as shown in figure 1, where, T_{s1} and T_{s2} are the sampling times of the first and the second zero-order-hold samplers respectively. The first sampler represents the output of the encoder-decoder position signal, whereas the second sampler represents the sampling time of a discrete derivative computer.

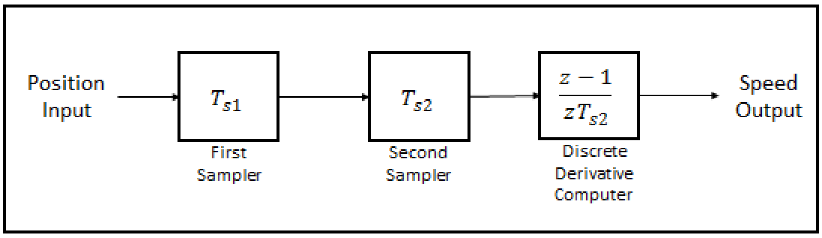

Figure 1: The process of discrete derivative computer block diagram.

There is no problem in computing the derivative, when the sampling time of the position signal is less or equal to the sampling time of the difference computer, this case is presented in figure 2. In other words, there is no problem in computing the derivative, when the sampling frequency of the position signal is higher or equal to the sampling frequency of the difference computer. On the other hand, when the sampling time of the position signal is larger than the sampling time of the difference computer or the sampling frequency of the difference computer is higher than the sampling frequency of the position signal, as presented in figure 3, the derivation of the speed will have some spikes at the time of incremental changes, or zeros when the zero order hold sampled position signal is constant between two samples of the difference computer.

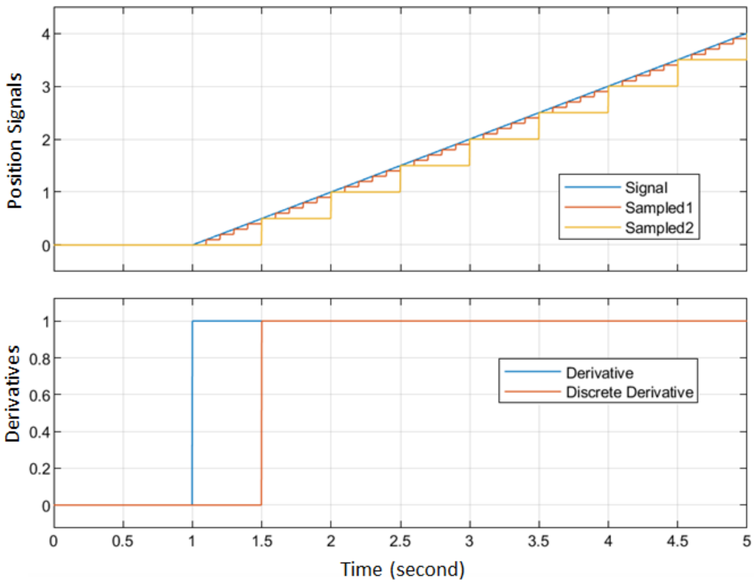

Figure 2: The case of sampling time ($T_{s1} = 0.1 < T_{s2} = 0.5$); or sampling frequency ($F_{s1} > F_{s2}$)

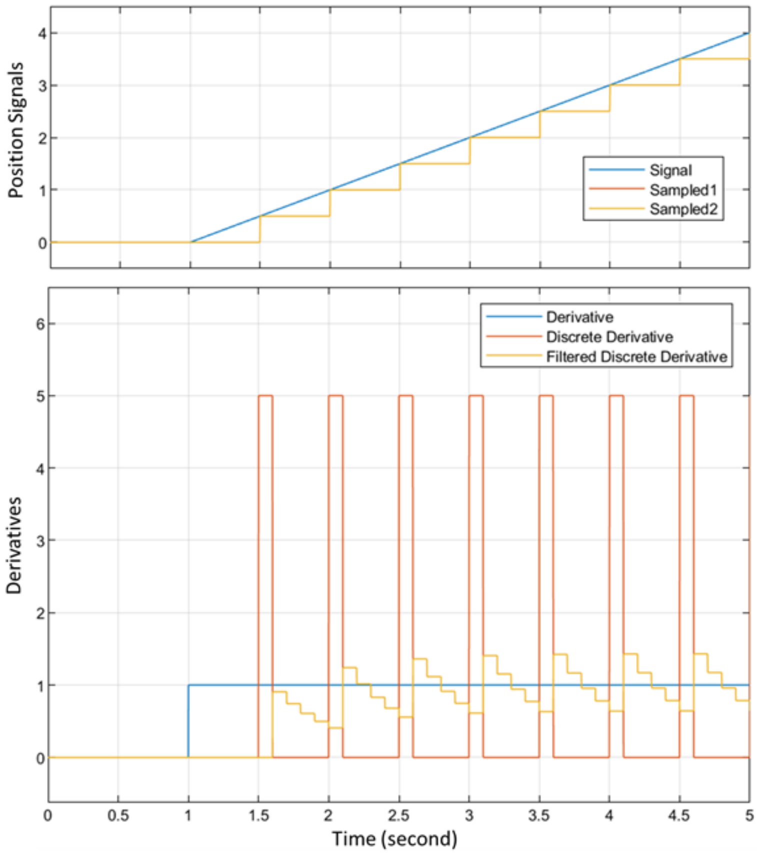

Figure 3: The case of sampling time ($T_{s1} = 0.5 > T_{s2} = 0.1$); or sampling frequency ($F_{s1} < F_{s2}$)

One of the ways to solve this problem is simply by computing the average, for example, using a low pass filter. To make the output of the difference computer very smooth, a very low cutoff frequency is used, but the filter will give a very sluggish response and a large delay if the signal is used in closing the feedback loop, which causes the feedback system to be complex and unstable. Meanwhile, using a high cutoff frequency will reduce the delay, but it will not smooth the spikes properly, as shown in figure 3, if used in the feedback loop it will affect it and drive it to oscillate. One solution is to use a speed observer to enhance the quality of the computed speed signal; for example, an intensive study was done on observer empirical optimization in open and closed [3], which suggests that an observer with a good internal model and poor measurements could give an optimal state estimation when its gain were set relatively low. Generally, to obtain a better speed measurements from quadrature sensors, one can either count the period in low speed ranges, count the frequency in high speed ranges or a combination of both methods to obtain the best results in intermediate ranges, but these are more complex and demanding solutions [7, 8, 9, 10, 11].

Actually, the sampling time of the first sampler is dependent on the speed in the case of encoder-decoder position sensor, this means that the sampling time is variable during the operation and can be higher and lower in comparison to the second sampling time of the discrete derivative computer, for example, the speed at 54 degrees per second for 20 ppr (18 dpp) sensor is 3 pulses per second, which is 3 Hz, resulting in three steps per second with a sampling rate of 0.333 second. While at speed 180 degrees per second the sampling time becomes 0.1 second at 10 Hz frequency. In the next section, the introduced digital speed sensor is used to study the impact of low quality and low resolution sensors on the performance of feedback control systems.

III. DIGITAL SPEED SERVO CONTROL

In this section, a digital PID controller is used to control a rotational speed servo control system representing a simple pseudo geared motor system, the parameterized model of which is shown in figure 4. The speed of the output shaft is measured with an ideal speed sensor and used to close the loop of the feedback speed control system, as shown in figure 5A, the controller is a discrete PID controller with the parameters (P=10, I = 20, D = 0) and the controller sampling time is equal to 0.01 second, the feedback system with an ideal speed sensor is functioning as reference to the following systems.

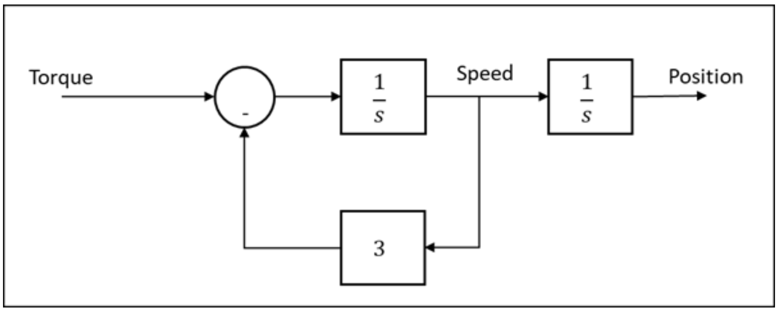

Figure 4: The pseudo geared motor system model.

However, in the feedback system shown in figure 5B, the output shaft speed is measured by a speed sensor, introduced in previous section, which consists of a low resolution encoder-decoder position sensor combined with a discrete derivative computer with a pre filter, as shown in figure 6. The internal block diagrams of the encoder-decoder position sensor are presented in [1]. The measured output is used to close the loop of the speed feedback control system using a discrete PID controller with the same parameters as the previous reference feedback system with an ideal speed sensor, as shown in figure 5A.

Moreover, a discrete observer is implemented to observe the pseudo geared motor system speed using its input torque and the measured speed of the pseudo geared motor using the speed sensor as shown in figure 5C. The speed observer is designed to have the model structure and the discrete parameters of the pseudo geared motor system sampled with zero order hold at a rate of 100 samples per second, as shown figure 7. Furthermore, another discrete speed observer is designed by adding a discrete integrator to the previously presented speed observer, see figure 8, and implemented to estimate the speed by using the input torque and the measured position from the encoder-decoder sensor, then the estimated speed signal is used to close the loop of the digital speed feedback control system with the same predefined discrete PID controller parameters, see figure 5D. To reduce the impact of the low resolution and low quality sensor signal on the speed feedback system, both observers are designed to pay more attention to the internal model rather than the measurements by setting their gains to relatively very low values as concluded in reference [3].

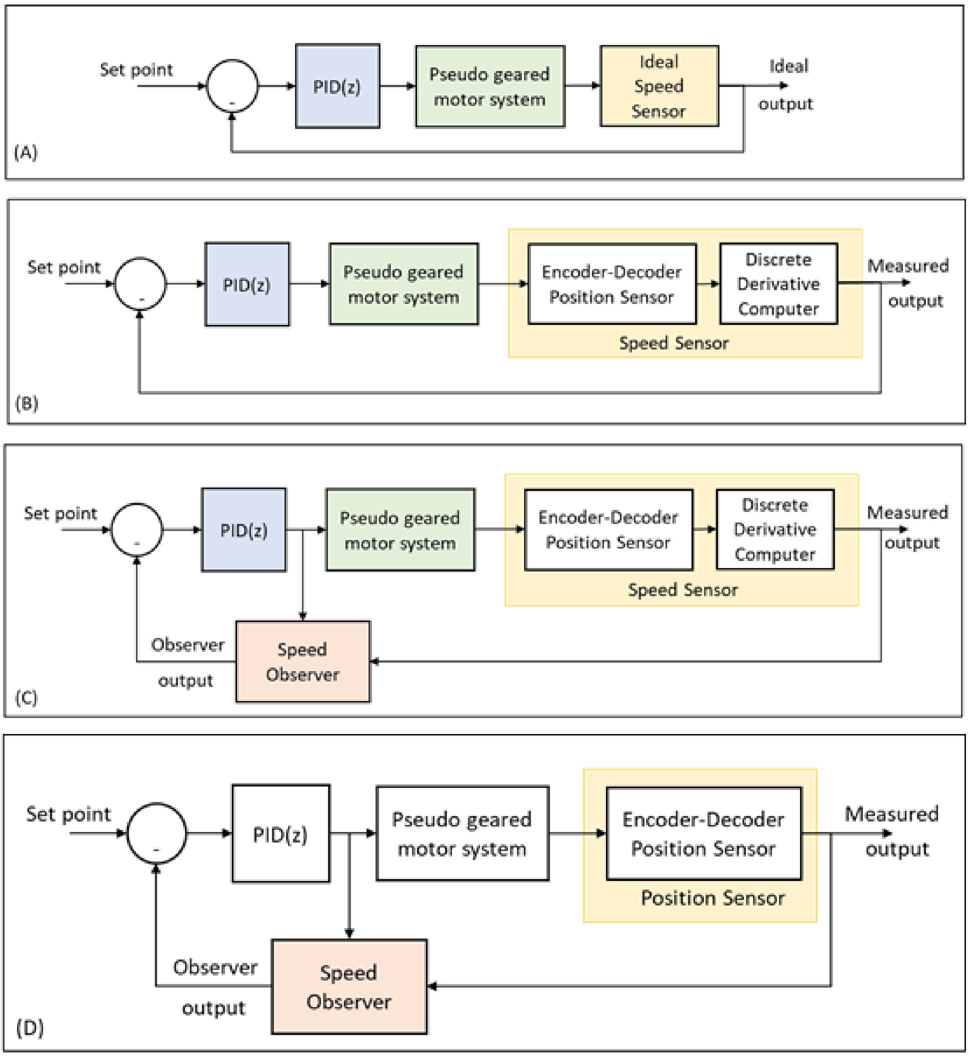

Figure 5: (A) feedback using an ideal speed sensor, (B) feedback using a speed sensor, (C) feedback using an observer with a speed sensor, and (D) feedback using observer speed based on the position sensor.

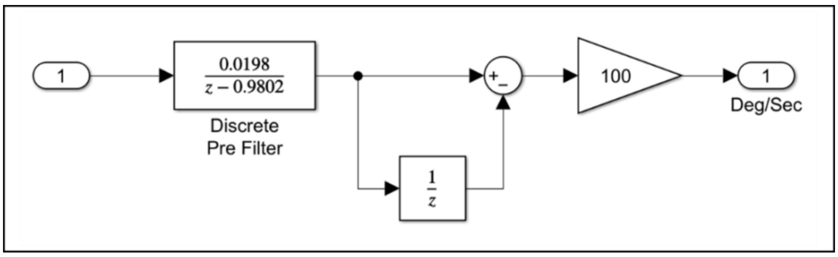

Figure 6: The discrete derivative speed computer with a pre filter.

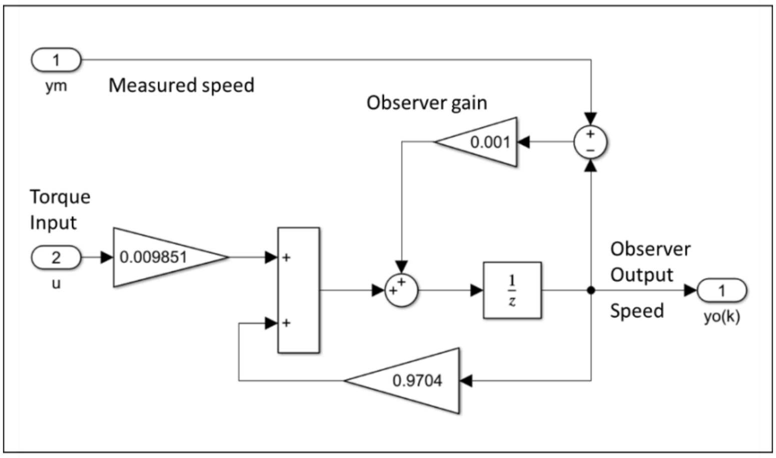

Figure 7: The discrete speed observer based on speed measurements.

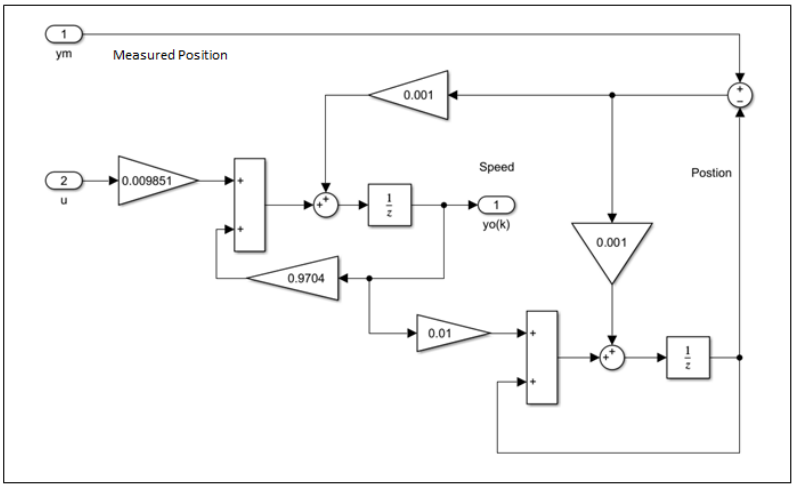

Figure 8: The discrete speed observer based on position measurements.

Figure 9A shows the step response of the digital speed feedback control system with an ideal sensor, as presented in figure 5A, to work as reference to the actual output and measured output step response of the digital speed feedback control system with speed sensor of figure 5B. From the figure 9A, it can be seen that the actual and the measured outputs of the system of figure 5B system are different because of the low resolution of the encoder-decoder position sensor, and the approximation of the speed signal by the discrete speed computer drives the feedback system to oscillate. Moreover, figure 9B presents the step response of the figure 5C system, where the observer output is used to close the loop of the speed feedback control system, this shows that the actual output response becomes very close to the reference feedback system with the ideal speed sensor, this is because the observer speed model parameters are perfect which allows to set the speed observer gain to very low value, this makes the speed observer to trust the model more than the low quality measurements. Furthermore, figure 10A presents the output responses of the feedback system in figure 5D and compares them with the output responses of the feedback system with the ideal speed sensor shown in figure 5A. The response shows that the observer based on the position measurements performs better that the speed observer based on the speed measurements in terms of closeness of the actual output step response of figure 5D to the reference system output of figure 5A. Figure 10B shows the switching of the feedback signal, at approximately 10 seconds, from the speed sensor to the observer. This illustrates the case when the observer model does not have the ideal parameters, which means that the observer model parameters are different from the pseudo geared motor model parameters. Therefore, the observer gains are designed here to make the feedback system to have no or less oscillations induced by the low quality sensor measurements. This is a practical case, where normally the observer model is not one hundred percent exactly as the pseudo geared motor system, but it can still be used to enhance the poor measurements of low resolution sensor. This is the main conclusion, where it can be used in practice to reduce effect of a low resolution sensor on the performance of a feedback control system.

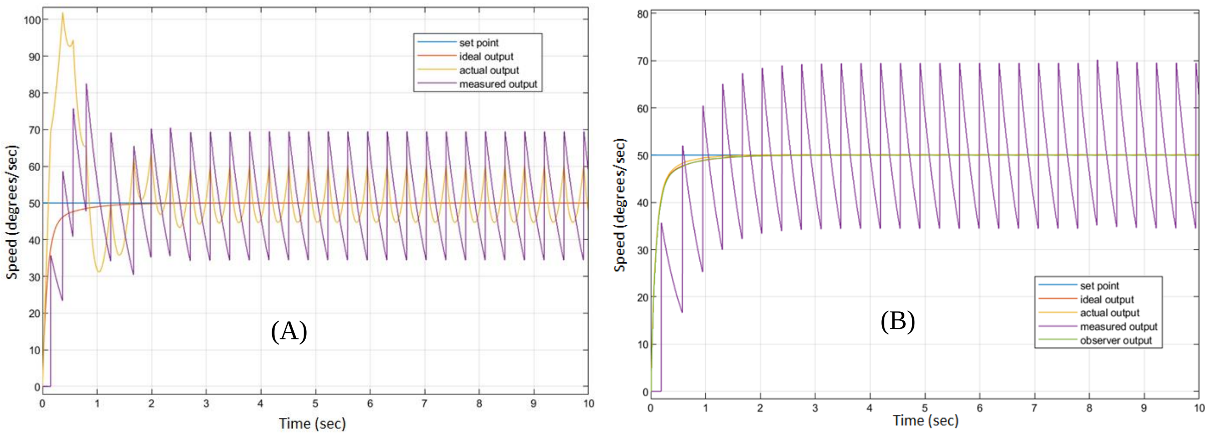

Figure 9: (A) digital speed feedback control system using speed sensor, and (B) observer speed feedback based on speed measurements.

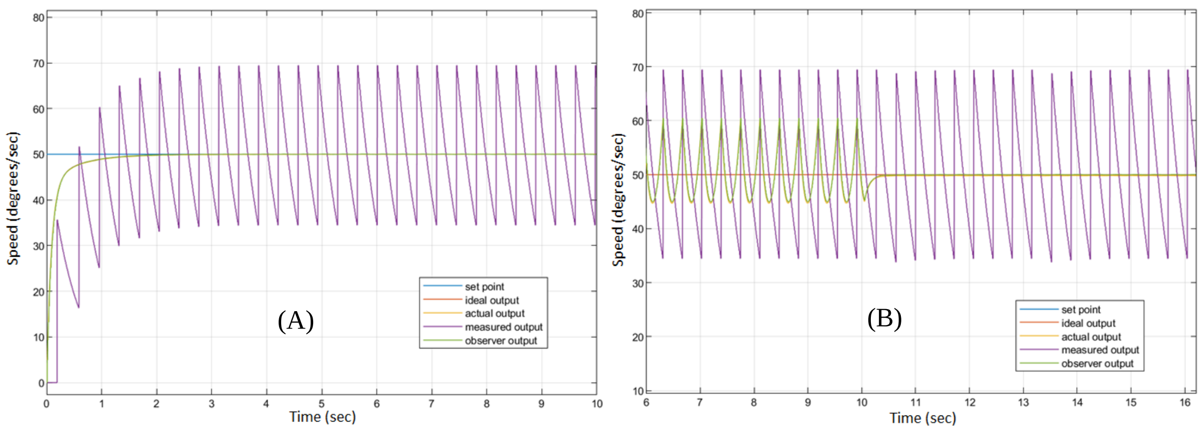

Figure 10: (A) observer speed feedback based on position measurements, and (B) observer speed feedback based on position measurements with imperfect observer model parameters.

IV. REAL TIME HARDWARE IMPLEMENTATION

The rotational speed servo control system is realized by controlling the rotational speed of the geared DC motor through the dual H-bridge L298N unit, and the output shaft rotational position is detected by a simple rotary quadrature encoder switch KY-040 unit, which has a very low resolution of 20 pulses per revolution. The control algorithms were developed and tested in Matlab-Simulink graphical programming environment and then compiled and run in real time using Arduino Mega 2560 board; the details of the mechanical and electrical interconnections of the test platform hardware are shown in section V of reference [1]. The block diagram of the rotational speed servo control system is presented in figure 11, where a digital PID controller is used to control the rotational speed of the geared motor output shaft, either by selecting the measured speed (deg/Sec) or the observer speed to close the feedback loop, which is activated manually by a switch.

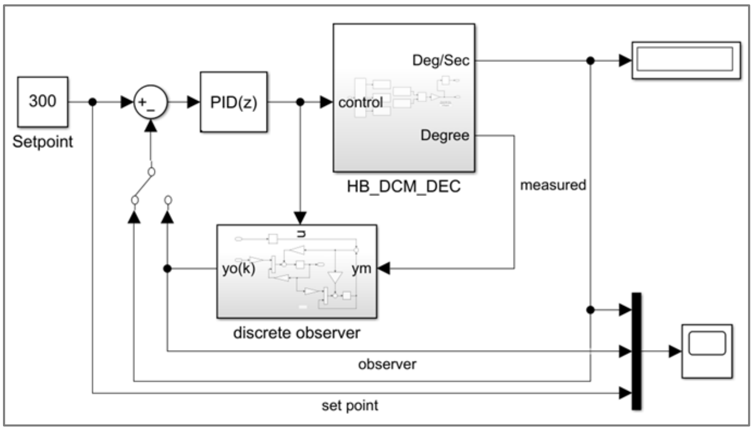

Figure 11: Rotational speed servo control system block diagram.

The block diagram of the subsystem (HB_DCM_DEC) combines the H-bridge drive blocks that control the torque and the direction of the DC motor, as well as the incremental position decoder and the speed computer, as shown in figure 12. The discrete observer subsystem was designed as presented in figure 5D, and the parameters of the observer model were identified offline from identification experiments by collecting input output data of the open-loop geared motor system; then, the best fit of the discrete linear model of the open loop system was chosen.

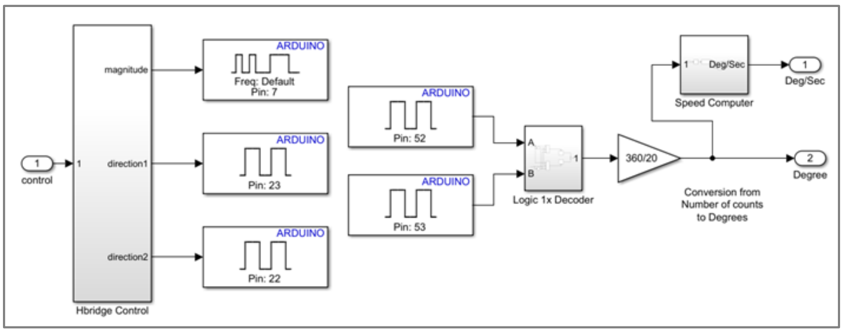

Figure 12: The internal block diagram of the subsystem (HB_DCM_DEC).

At the beginning, the digital PID controller uses the measured speed to close the loop of the feedback speed servo control system, and then at about time 63 seconds, the manual switch is switched to select the observer output to close the feedback loop. The output response of the system is plotted in figure 13, which shows that at the beginning, the output speed is affected by oscillations injected by a low quality position sensor and the digital speed computer; then, when the observer is selected to close the loop, the actual and the observer outputs become to have less oscillations, and therefore, the feedback system performance is improved. Note that the actual output is not available, as in simulation, but it can be sensed, heard and seen from the motor operation, and its speed becomes very smooth and steady.

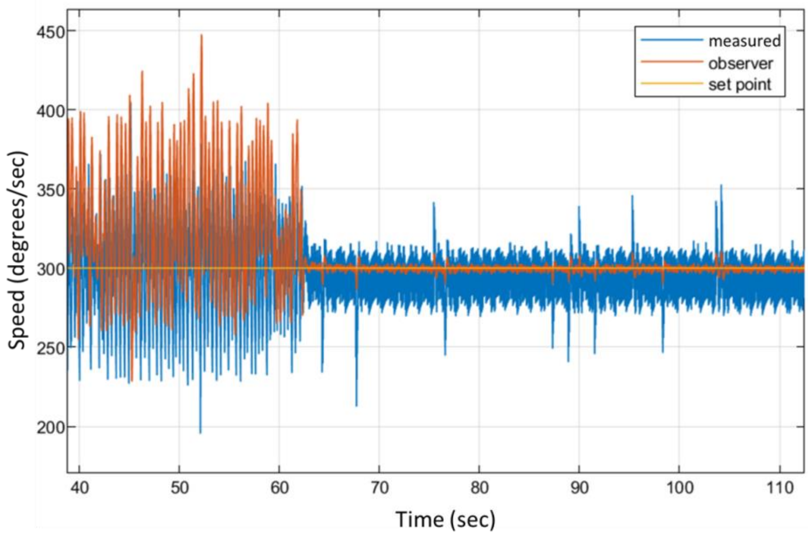

Figure 13: The measured speed and the observer speed response to the set point.

V. CONCLUSIONS AND FUTURE WORK

In this work, the impact of using a low-quality and low-resolution sensor on a feedback system is studied in general and on the performance of a feedback rotational speed servo control system in particular. The simulation experiments show that the measured output definitely diverges from the actual output owing to the low resolution errors and the low quality of signal conditioning and computations. The performance of the feedback rotational speed servo control system using this measured output suffers severely from low resolution position sensor errors and oscillations induced by low quality signal conditioning and computations of the implemented speed computer.

Nevertheless, the performance can be enhanced by implementing a low gain observer under the condition that the observer internal model can provide a good approximation to the real plant characteristics, particularly around the operating region. This has been demonstrated in simulations and in real-time control applied to real hardware platform experiments. The performance enhancement of feedback control system owing to implementation of the low gain observer depends heavily on how good the internal model can approximate the real plant. Perfect enhancement can be achieved if the internal model is perfect. This means that the investment of time and effort in offline system identification to obtain a good model will lead to a better performance, if the option of replacing the low resolution sensor with higher one is not available, particularly with good quality signal conditioning and computation methods.

Furthermore, as future work, the control algorithms are going to be devised to make the design procedure simple, systematic and more attractive to practical control engineering, starting sequentially from sensor evaluation, observer internal model identification and observer gain determination to obtain the best performance from the feedback control system.

Finally, the price for better performance has to be paid, either in a high quality sensor or in a very good observer model; otherwise, a compromise between them has to be found.

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