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The Real-time Network Control of the Inverted Pendulum System Based on Siemens Hardware**

1. Introduction

The pendulum on a cart system is often regarded as an algorithmic pattern (called a benchmark) [3]. When considering only the control simulation based on a model it is generally ignored the entire hardware layer and software responsible for the experiment carried out on a real object in real time [2]. In the presented case, the intention of the authors is substitutions of all possible hardware and software elements of the pendulum on a cart system for the appropriate replacement to the SIEMENS elements. Therefore, not only the control algorithm is stored in a programmable logic controller SIMATIC S7-1200, but it is also the flat motor converted to the servo drive SINAMICS S110 cooperating with synchronous motor and resolver. All these elements are SIEMENS origin. New equipment makes it possible to compare the two modes of communication. The first is the use of a high-speed counter output mode PTO (Pulse Train Output) and the other is a PROFINET I/O with cyclic exchange of information between devices. In experiments of increasing the amplitude of oscillation and stabilizing of the pendulum at the upright unstable equilibrium points the attention is drawn to the exceptional use of servo tasks. Precisely, there are operations generally not performed by the servo i.e. forcing the engine to very slow reversing movements (especially in the task of stabilizing the pendulum in the upright positions). These operation modes are prepared in advance and stored in the servo SINAMICS S110. In fact, many of servo features have to be pre-empted, so the servo remains only sensitive to changes in the angle of the pendulum and the position of the cart on the rail. Since the network control system using PROFINET I/O performs flawlessly and fully repetitively

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complex and difficult control tasks maintaining the 2 ms time-regime then it may be presumed that the PLC and SINAMICS Siemens servo system are also capable of successful execution of a much simpler standard control functions.

2. The set-up description

A modified version of the laboratory inverted pendulum suspended to a cart is used in the experiments. The original pendulum hinged to a cart is driven by a DC motor powered by a dedicated controller. A real-time control is implemented using an I/O measurement board and a PC equipped with the MATLAB/Simulink software together with the relevant toolboxes [5]. The structure of the modified system is shown in Figure 1. Instead of the DC motor with the power interface the industrial Siemens servo is used operating in the speed mode. The servo consists of a drive system SINAMICS S110, synchronous motor 1FK7 and resolver. The servo will be described in section 2.1. A control algorithm is running on the PLC Siemens S7-1200 PLC. The control signal generated by the PLC controller is sent in two ways. The first uses a high-speed counter output mode PTO (Pulse Train Output) also known as PFM (Pulse Frequency Modulation). In this mode, the control signal is proportional to the frequency of the pulses at the first output (Puls), and the direction of rotation depends at the second output (Direction). Another way to communicate is to use a PROFINET I/O, which allows for a cyclic exchange of information between devices with a maximum period of 2 ms. Information about the cart position and pendulum angle is measured by two incremental encoders operating in the quadrature mode and is sent directly to the PLC. The applied encoders have 12-bit resolution.

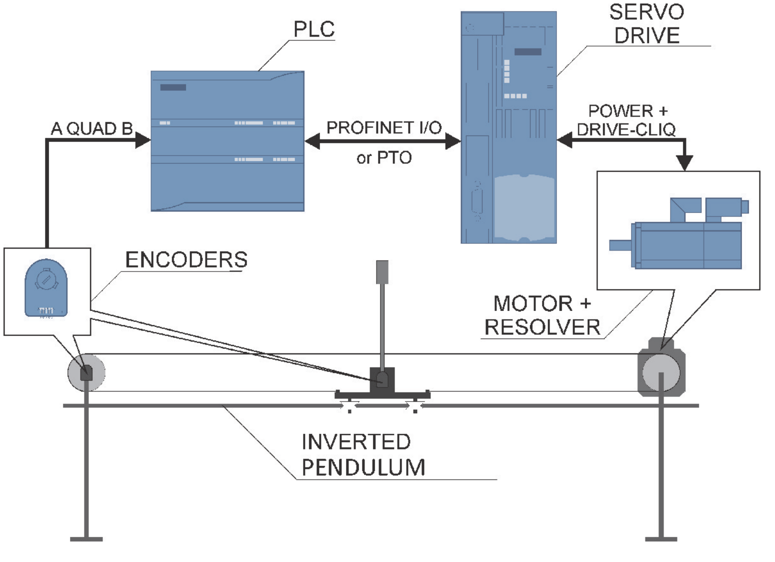


Fig. 1. Components of the setup [5]

2.1. The industrial servo SINAMICS S110

The used SINAMICS S110 servo drive [6] provides the basic functionality of single-axis positioning in drive systems. However combined with the master control system SINAMICS S110 enables the advanced motion control tasks. In this system there are three control algorithms:

– A sensorless speed control mode without an encoder. The current position of the motor shaft is reconstructed from the mathematical model of the motor. The control goal is to maintain the desired motor speed.
– Sensor speed control mode with an encoder/resolver. The control goal is to maintain the desired motor speed.
– Sensor torque control mode with an encoder/resolver. The control goal is to maintain the desired motor torque.
– U/f control – open loop control for diagnostics.

The servo controller can work with synchronous and asynchronous motors. The motor used in the experiments is 1FK7 synchronous motor with a nominal torque of 0.16 Nm and nominal rotation speed of 6000 rpm. The motor is integrated with the resolver with 3 poles. The servomotor and driver are connected via the DRIVE-CLIQ interface. The interface provides means to read the motor electronic nameplate and to transmit a resolver signal.

2.2. The inverted pendulum control task

The control diagram of a modified inverted pendulum system is shown in Figure 2.

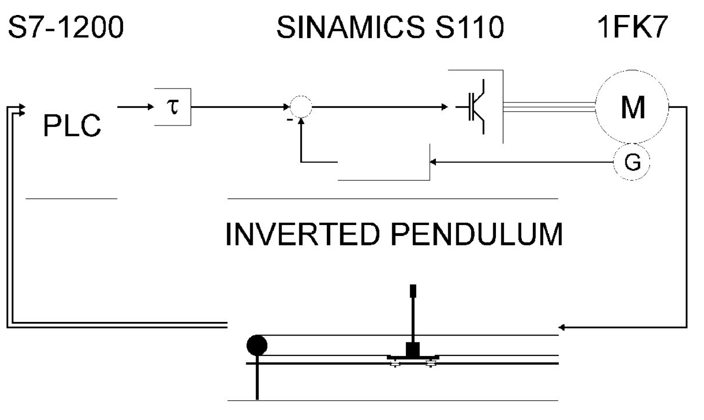


Fig. 2. A simplified block diagram of the control system

The diagram can be divided into two feedback loops. The first is the external loop. Measurements from the encoders related to the pendulum angle and cart position on the rail go to the PLC where the control is calculated. According to the current state of the pendulum it is either swung up or stabilized in the upright position of equilibrium. Then, the control signal is sent to the drive to the internal regulation system – the second control loop. An error between the control set-point signal and the current speed of the motor shaft reconstructed by the resolver is converted to the current control signal implemented then by the power interface. In a classic inverted pendulum system the control value derived directly from the controller goes to the power interface. The use of the SINAMICS S110 servo controller makes impossible to open the internal loop except the diagnostic U/f control signal. The diagnostic signal is not suitable to achieve sufficient growth of energy to bring the pendulum to the upright unstable equilibrium point. As a result, the pendulum control system has an additional controller compared to the classic scheme. The structure of the internal control system has been adapted to the requirements of the inverted pendulum control.

2.3. Configuring the drive controller

The STARTER software tool has been used to configure the SINAMICS S110 drive controller. The software allows for easy configuration thanks to a readable layout. In Figure 3 a part of the diagram responsible for the current control is shown.

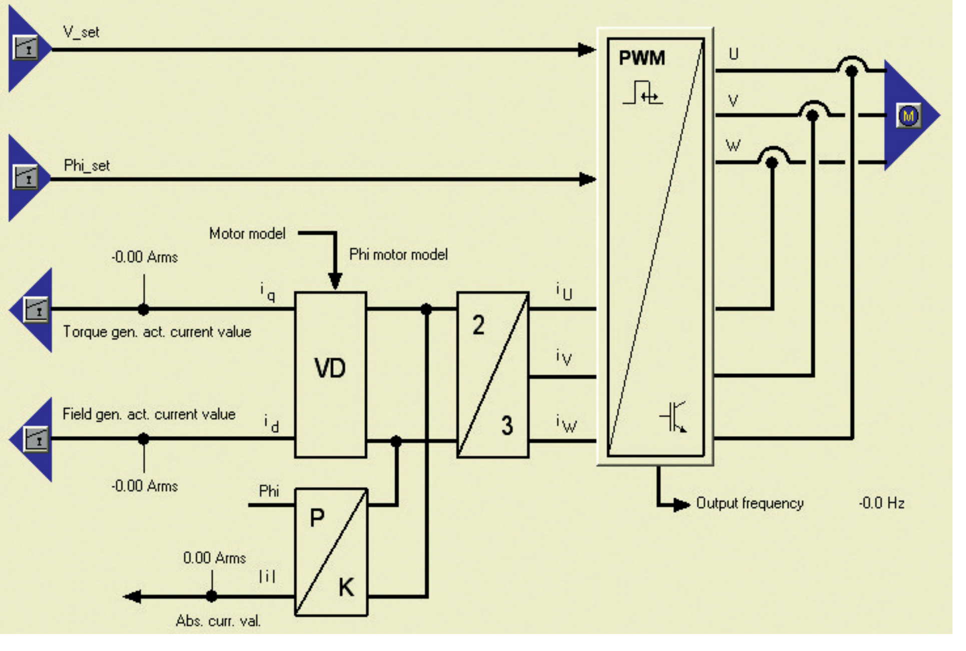


Fig. 3. A part of the STARTER diagram showing the current control

In order to achieve the desired dynamic of the servo the signal filtering of the set-point control is disabled. Also the dynamic adaptation of the speed controller parameters is disabled. In addition, a part of the speed controller responsible for integrating the input is disabled to avoid any impact on the cart motion in the case of the zero value. The proportional controller gain is set to the maximum value that does not cause oscillations.

3. Control algorithm

3.1. A rule based algorithm

The pendulum on a cart system, a seemingly simple, but represents a non-trivial non-linear dynamics of the fourth order with infinitely many unstable equilibrium points [2]. With one control one needs to interact simultaneously on two objects, directly on the cart and indirectly on the pendulum.

Table 1
Rule-based algorithm

Limiting the cart motion to the rail runway range
If $\lvert x_1 \rvert - Z > 0$ (1)
then $u = -u_{\max}^{\mathrm{STAB}} \operatorname{sign} x_1$ (2)
Stabilization of the pendulum in its upright unstable equilibrium points
If $\lvert x_2 \rvert - S < 0$ (3)
then $u_r = K_1(x_1 - x_1^f) + K_2 x_2 + K_3 x_3 + K_4 x_4$ (4)
if $\lvert u_r \rvert + F_s > u_{\max}^{\mathrm{STAB}}$ (5)
then $u = u_{\max}^{\mathrm{STAB}} \operatorname{sign} u_r$ (6)
else $u = u_r + F_s \operatorname{sign} u_r$ (7)
end
Increasing an amplitude of the pendulum oscillations together with reduction of the angular velocity in achieving the upper unstable equilibrium position
elseif
$\frac{1}{2} x_4^2 + 9{,}81 \cdot 3{,}2(\cos x_2 - 1) > 0$ (8)
then $u = 0$ (9)
else $u = -u_{\max}^{\mathrm{POST}} \operatorname{sign}\left[x_4 \left(\lvert x_2 \rvert - \frac{\pi}{2} \right) \right]$ (10)
end

The cart while moving must not exceed the rail limits and at the final control time it has to be stopped in the middle of the rail. The pendulum, outside the upper stability zone has to increase the amplitude of oscillations and at the upper zone inversely, has to reduce the amplitude of oscillations until a resting state. The algorithm shown in Table 1, consist of rules. The angle of the pendulum is in the [–π, π] radians range. The Z parameter is set at a value less than half the length of the real rail traction. If the car exceeds the assumed rail traction (1), the force applied to the cart pulls it to the center of the rail (2).If the pendulum is in the upper stability zone S in a neighbourhood of an upright equilibrium point (3), the linear controller operates. It compensates the static friction of the cart and it can saturate (4). K = [K1, K2, K3, K4] is a gain matrix in the feedback paths calculated by the solution of a suitable linear-quadratic problem. If the linear control achieves limits as to not exceed the limits is subject to saturation. The saturated control with taking into account the static friction F_s, takes place after reaching the limits $[-u_{\max}^{\mathrm{STAB}}, u_{\max}^{\mathrm{STAB}}]$ (5). At saturation, the output will be controlled by the absolute value of $u_{\max}^{\mathrm{STAB}}$ (6), and in the absence of saturation is taken from the control range $[-u_{\max}^{\mathrm{STAB}}, u_{\max}^{\mathrm{STAB}}]$. There are effects difficult to be modelled. Thus, the cart dry friction is compensated by adding to or subtracting from the control a constant value. If the linear control is positive, its value is increased by adding constant F_s, to overcome the dry friction. A negative control is decreased by subtracting a constant value F_s (7).

If the pendulum is outside the stabilization zone, it will be brought to the zone (by increasing the amplitude of oscillations). In order that the pendulum has reached the upright position, with no tendency for further rotating, the algorithm has to ensure that the angular velocity of the pendulum in the upright position was close to zero. The algorithm checks at each sampling step, if the kinetic energy of the pendulum is sufficient to raise the center of gravity of the pendulum in its upper position (8). If so, control is switched off and takes a value of zero (9). A rule to increase the amplitude of oscillations has a simple form. The control is a bang-bang. Switching times are a function of the angle and angular velocity sign of the pendulum (10).

3.2. Implementation of the control algorithm on PLC

The block diagram of the control algorithm running on the PLC is shown in Figure 4. Functionally the algorithm consists of the main and measurement loops. The main loop checks to see whether the cart position limits on the rail are not exceeded. It selects the operating mode of the pendulum at the upper position (Pendulum) or at the lower position (Crane) and activates the proper position controller. In the final stage of the main loop the ultimate value of servo control including restrictions imposed is calculated. There is an update of the variable corresponding to the control and activation of the SINAMICS driver. The execution time of the main loop is constituted merely by the cycle time of the PLC. The measurement loop is reading the angular positions from the high-speed counter module, connected to the incremental encoders. These values are converted to physical units of the pendulum angular position (radians) and the cart position (meters). Then the angular speed of the pendulum and linear speed of the cart are reconstructed respectively. Variables which store information about the positions and speeds are updated in the last stage of the measurement loop.

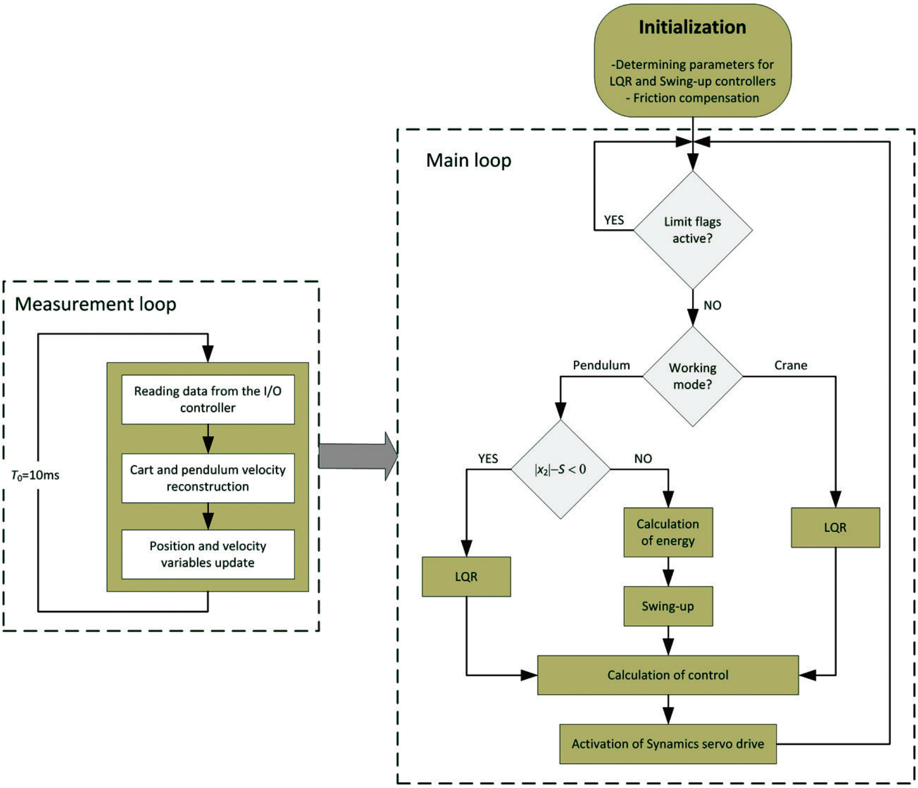


Fig. 4. Block diagram of the control algorithm

These variables are used in the main loop of the program to determine the servo control value. The measuring loop is executed cyclically with a period of T_0 = 10 ms. The controller is built in the environment Totally Integrated Automation Portal (TIA) SIEMENS. The project consists of modules responsible for the implementation of the various stages of the algorithm. The modules are implemented in the form of programs in the ladder logic or Structured Text language. How to write a ladder algorithm in the TIA environment is shown in Figure 5.

Some of the blocks are used to implement the algorithm. Others are equally important in view of the implementation of measurement and control connections. The motor of the inverted pendulum is controlled via a PWM wave form with a four-transistor H-bridge motor. The rotation direction is controlled by an independent digital output. Built-in control blocks with generation pulse signals enable to control the motor using PWM waves with frequencies lying well above harmful to the human ear acoustic frequencies. Measurements of both the cart position and the pendulum angle are implemented using the quadrature incremental encoders. They generate 4096 pulses per revolution, allowing a resolution of cart position equal to 0.0595 millimetre and 0.0879 degree respectively. The model does not include the speed measurement systems. The speeds, both of the cart and pendulum, reconstructed from the position measurements, are necessary for regulator operation.

The speed reconstruction based on the positions is trivial for long periods of the sampling or high-speeds because the number of pulses generated by the encoder between consecutive sampling periods is high. Unfortunately, in the case of the pendulum especially near the upper point of equilibrium, the required sampling rate is fast and the cart and pendulum speeds are small. We are facing with a situation where the sampling periods between successive encoder counters are changing the value to two, to one, to no pulse at all. Successful control depends on several factors. These are: a properly selected sampling period (faster sampling does not necessarily improve the job), an effective speed reconstruction algorithm and a properly identified and tuned model.

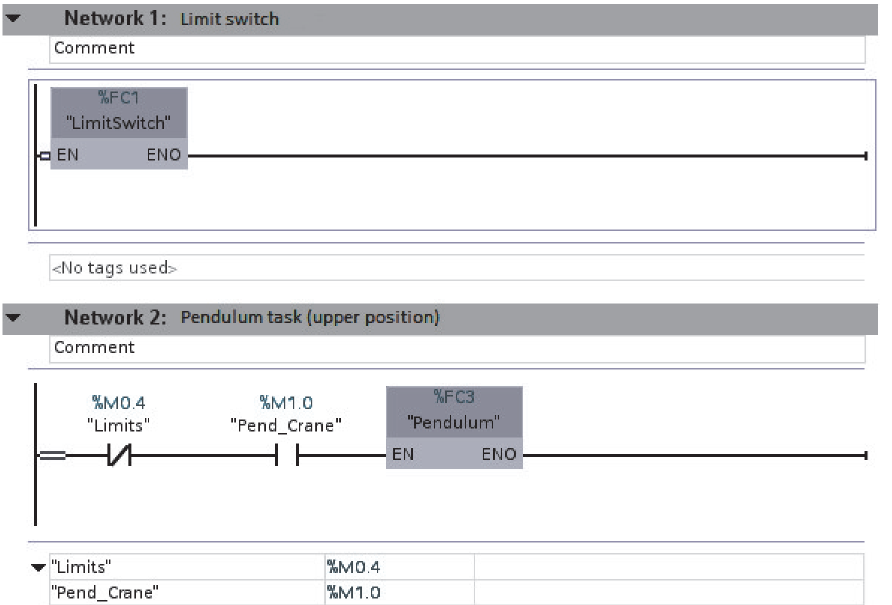


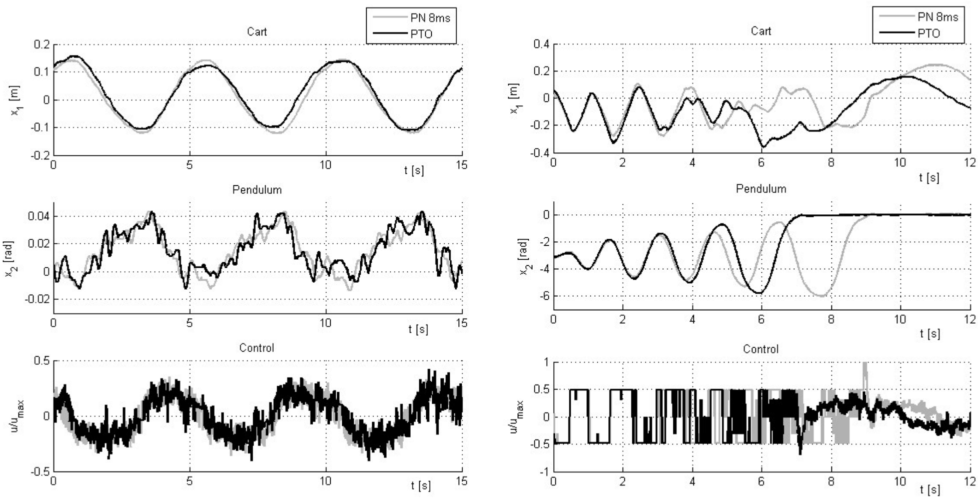
Fig. 5. A part of the algorithm stored in the ladder logic in the TIA environment

4. Experiments

Experiments are carried out on the laboratory networked inverted pendulum control system (Fig. 2) for the two control modes:

1. Autonomous, which uses only the PLC controller with high-speed counters working in the PTO mode(PWM signal with variable direction).The sampling rate is set at a value of 10 ms.
2. Networked with PROFINET IO. In this mode, the experiments are performed for two values of the period updating of the frame containing the PROFINET control: 8 ms and 2 ms.

The pendulum stabilized near the upper unstable equilibrium point is a very demanding system with regard to the stability of the generated time control. The loss of control leads to the pendulum fall down allowing a visual assessment of the control quality. A typical experiment is to swing up the pendulum and keep it in the upright position while maintaining the cart in the middle of the rail. A behaviour similar to the typical experiment is the one shown in Figure 6.



Swinging Stabilization

Fig. 6. The inverted pendulum control experiment

Figure 6 shows the cart position and the pendulum angle and control u during the experiments. Initially the pendulum is in a lower equilibrium position of equilibrium described as +/–π rad. Cart motion pumps energy to the pendulum driving it close to the stabilization zone near the 0 rad angles.

5. Conclusions

The presented configuration of the control system, including network-connected PLC and servo controller is extremely complicated compared to the requirements of the control system of the inverted pendulum. The control object is selected solely because of the sensitivity of the signal decays and serves as an assurance tester of the control distribution in a distributed configuration. The SINAMICS S110 drive controller is inherently designed for servo positioning operations, while providing integrated security features. This functionality is important for industrial applications. Use this driver for the implementation of rule-based algorithm for the pendulum on a cart system confirms that the modified system is capable of accurate and quick response. During the experiments, there was no qualitative difference in the control of the pendulum in a distributed configuration with PROFINET and controlled directly from the PLC.

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