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PAPER

Integrated SolidWorks and Simscape platform for the design and control of an inverted pendulum system

Ahmed Alkamachi[1]

A single inverted pendulum on a cart (SIPC) is designed and modeled physically using SolidWorks. The model is then exported to the Simulink environment to form a Simscape model for simulation and test purposes. This type of modeling uses a physical grid tactic to model mechanical structures. It requires connection of the physical elements with physical signal converter to define the implicit system dynamics to be modeled. The integration between the SolidWorks and Simscape eliminates the need of deriving the mathematical model and provides a platform for the rapid controller design for the system. State feedback control scheme is proposed, designed, and tuned aiming to maintain the pendulum in the upright place while tracking the desired cart position. Several simulation cases are studied to prove the controller abilities. In order to examine the controller robustness, disturbance rejection and noise attenuation capabilities are also discovered.

K e y w o r d s: inverted pendulum on a cart, robust control, simscape modeling, SolidWorks, state feedback controller.

1 Introduction

Inverted pendulum system has been widely used to examine both classical and modern control theory due to its important characteristics of nonlinearity and underactuation [1, 2]. Controlling the inverted pendulum system is significant since it forms the basis of many important practical applications like rocket lunching stabilization, human like robot gait, wheeled mobile robot, pendubots, and building stabilization during earthquakes [3, 4]. The inverted pendulum applications require an accurate response with high overall system stability [5].

The SIPC is highly unstable and nonlinear [6]. It is considered as an underactuated system as it has a single control input versus two degrees of freedom (*ie* pendulum angle and cart position), therefore designing a suitable controller for such system is a challenge [7, 8]. This system attracts many researches since it is considered as the standard laboratory benchmark to understand and test control theories [9–12]. To design an effective controller for this system, an accurate model should be obtained. The equations of dynamics need to be derived manually, and then they should be arranged into a form that can be used into a block diagram representation. It is very difficult to understand how the physical components in this system are practically interacted. Obtaining the inverted pendulum model can be done either analytically by deriving the model mathematical representation using Euler-Lagrange approach [13] or with the aid of Simscape toolbox in Matlab [14, 15].

Many researchers developed Simscape models for different systems to understand their physical behavior [16]. Some of these models are hexapod robot [17], Sit-to-Stand Movement [18], Photovoltaic panel [19], and vertical walking three-linked robot [20].

The main contribution of this work is to integrate between the use of SolidWorks and Simscape as a recent inverted physical modeling method, and introduce a successful way for the model-based control algorithms design.

2 System design and modelling

The SIPC system consists of a rod attached to a cart that moves on a rigid surface as shown in Fig. 1. The aim of the system is to track a desired cart position while maintaining the pendulum in the upright zero inclination angle. To achieve this goal, an external horizontal control force U is applied to move the cart along the x direction. The output of the system is the cart position x and the pendulum angle α.

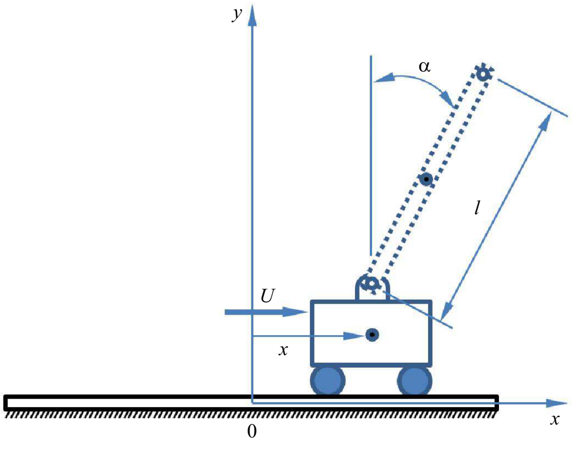

Fig. 1. A schematic drawing for the cart-pendulum system.

[1] University of Baghdad, Al-Khwarizmi College of Engineering, Mechatronics Engineering Department, Baghdad, Iraq, amrk1978@gmail.com

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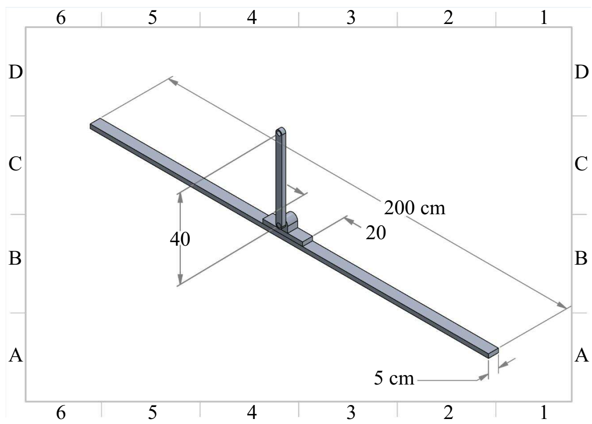

Fig. 2. Isometric sketch for the cart-pendulum system

2.1 *Mechanical specifications*

The cart in this system can move along the positive and negative x-axis direction with a range of ± 100 cm. The cart and pendulum are supposed to be made of aluminum alloy $(2.7\,\mathrm{g/cm^3})$, and their masses are 892 and 652 grams respectively. The length of the pendulum l is 40 cm. A SolidWorks isometric drawing for the system is shown in Fig. 2.

2.2 *Simscape multibody model*

The SolidWorks CAD design is imported into Matlab platform to obtain the Simscape model using Simscape Multibody Link plug-in. The interconnection between the mechanical parts is done using different types of joints to define the type of motion between the parts. The transformations between the 3D world and reference frames are made using rotation transforms blocks. Figure 3 shows how each mechanical part is linked to another. The revolute joint is used to connect the pendulum to the cart while the prismatic joint is used to connect cart with the fixed base track. The External Force and Torque block is added to apply an external disturbance force on the pendulum for the controller test purpose as it will be shown in the controller section in this paper.

3 Controller design

The system under study is controlled by applying a variable external force U on the cart. It is required to keep the vertical position of the pendulum while tracking the desired horizontal cart position. Due to the system structure, the upright position of the pendulum is the unstable position and this makes finding and designing a suitable controller a challenging task. The proposed controller in this work is a state feedback controller which will manage the applied force U in order to move the cart to its target while keeping the pendulum in an upright position. The proposed controller consists of a feedback block plus a feedforward gain compensator as depicted in Fig. 4.

The feedforward scaling compensator is used to overcome the high steady state error problem companion to the state feedback controller [21]. The feedback loop uses a state space controller that translates its two inputs (α, and x) into a feedback signal that adapts the input force U.

To start up the controller design process, some design requirements should be specified. Matlab is then used to adjust the state feedback controller and feedforward gain

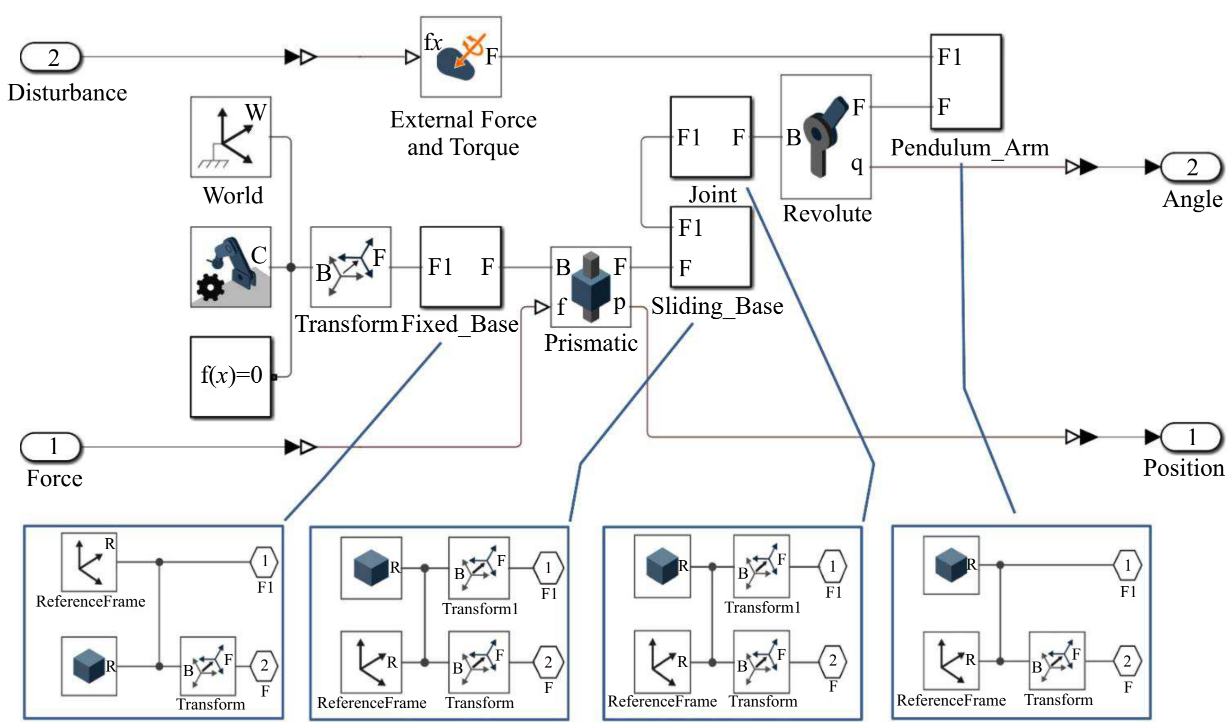

Fig. 3. Complete Simscape model for the SIPC system

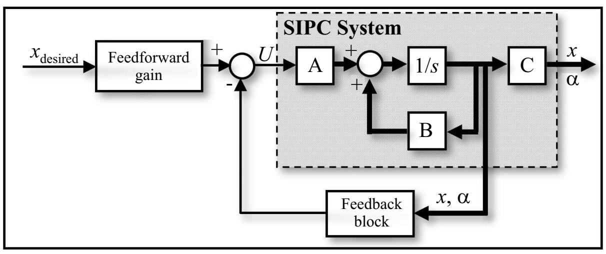

Fig. 4. The proposed control scheme block diagram

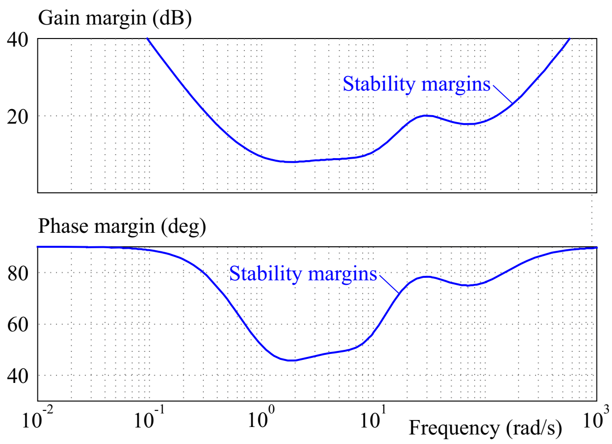

Fig. 5. Gain/phase margin plot for the system with the controller

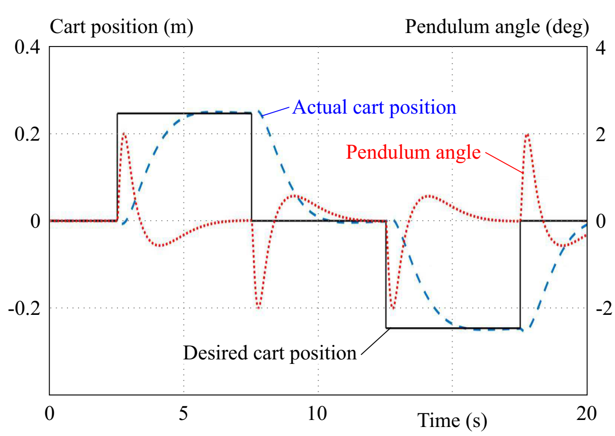

Fig. 6. Step input response plot for the SIPC system

parameters using "slTuner" tuning command. The design goals required to be achieved through the tuning process are as follows:

Goal 1: Settling time of 3 sec or less.

Goal 2: In order for the system to be robust, it should have no less than 5 dB gain margin and 40 deg phase margin.

Goal 3: An optimum Linear-quadratic-Gaussian (LQG) control is used to qualify the controller to reject the external disturbance dU that may be exerted on the pendulum head while guarantee that the applied force effort U will not exceed its limit. In our design, the LQG control law is proposed to be as follows

$$\int_0^\infty (15\alpha^2 + x^2 + 0.02U^2)\mathrm{d}t\,. \tag{1}$$

Goal 4: In order to obtain a soft transient response, another requirement is applied by setting up damping coefficient to 0.8 and the natural frequency of oscillation to 100 rad/s.

After specifying these four requirements, the tuning process is started and the following parameters are obtained.

Feedback block parameters:

$$\mathbf{A} = \begin{bmatrix} -115.92 & -9.11 \\ -656.29 & -97.54 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} -167.13 & 201.15 \\ 85.76 & 1612.24 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 824.97 & 113.61 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} 81.67 & -2035.35 \end{bmatrix}$$

Feedforward compensator gain $= -12.48$.

With these parameters, the gain/phase margin plot is depicted in Fig. 5. The plot shows that the minimum achieved gain margin is about 8 dB at 1.8 rad/sec, and the minimum phase margin is 46.7 degree at 1.75 rad/sec. It means that the phase and gain margin attained met the design requirement stated in goal 2 in section 3 of this paper.

4 Results and discussion

Simulation tests and results come up with a deep insights into the system action without the necessity to write the complex mathematical model of the system. This way of analysis also lessens the need for the physical system - which is mostly expensive - to understand and apply various control schemes.

For the purpose of assessing the controller ability and robustness, the simulation is divided into three phases:

Test 1: Step input response

The controller is examined on its ability to track a desired cart position. The controller generates a control signal to displace the cart to the desired position and at the same time balance the pendulum in its unstable upright position. Concerning the cart position response, there is almost no overshoot and the settling time is 2.4 s. The pendulum angle deviation is very small and it is within ± 2 deg in range 2.4 s. The system performance plot is shown in Fig. 6.

Test 2: External disturbance rejection

An external disturbance signal of 10 N is applied at the tip of the pendulum at a time shown in Fig. 7(a). Simulation result proves the controller ability to reject the disturbance signal. Hence, the controller is eligible to reveal the original cart position and to effectively balance the pendulum in the upright position. The system restores its states in about 3 s as shown in Fig. 7(b).

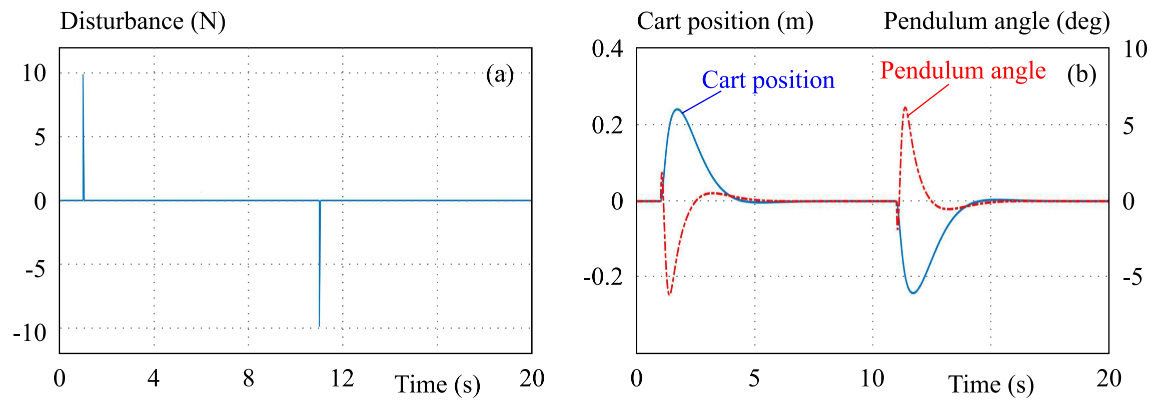

Fig. 7. Disturbance test plots. (a) – Applied disturbance signal, (b) – System response to the disturbance signal

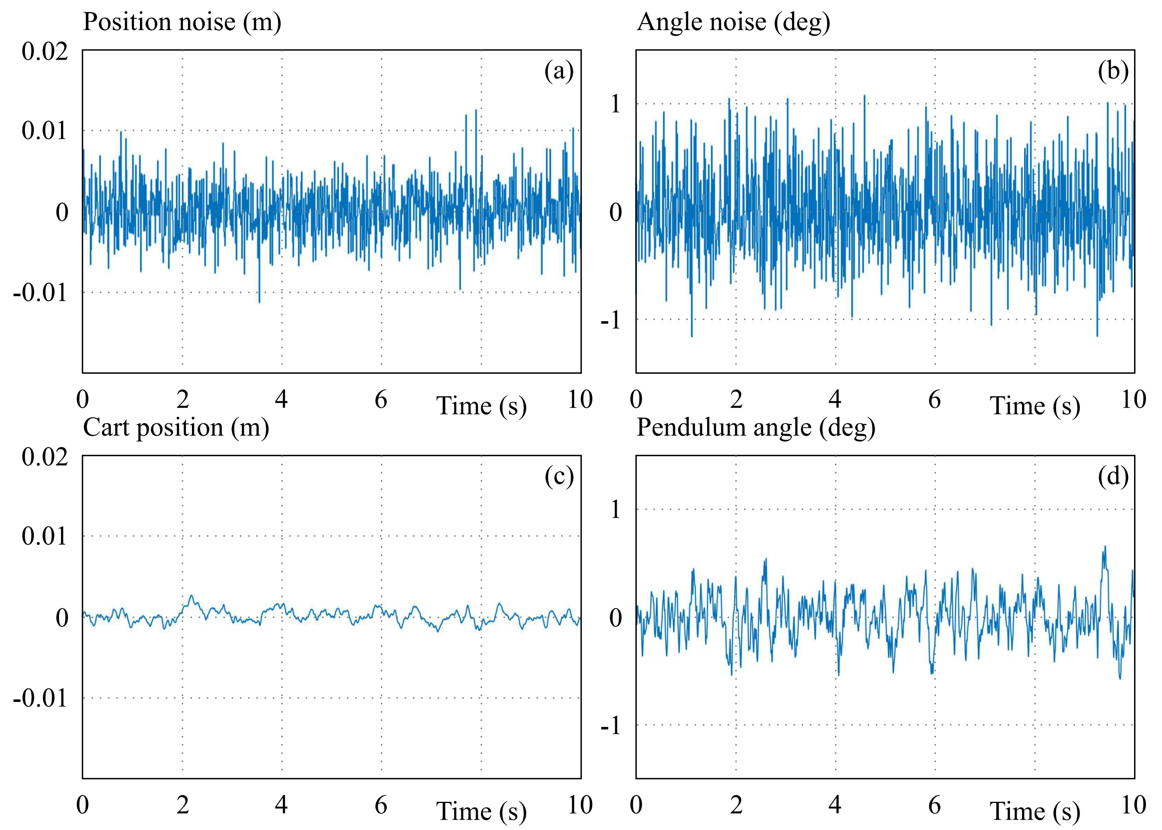

Fig. 8. Sensor noise test plots. (a) – noise signal added to the cart position state, (b) – noise signal added to the pendulum angle state, (c) – deviation of the cart position, (d) – swinging of the pendulum angle

Test 3: Sensor noise attenuation

It is an essential test since most of the sensor signals are combined with a white noise [22]. A white Gaussian noise signal, shown in Fig. 8(a) and Fig. 8(b), is added to the feedback position and angle signals to mimic the sensors noise. The controller shows a very good noise attenuation property by keeping the cart in its position with a very small deviation in position and pendulum angle. The cart swings with ± 2 mm from its initial, while the pendulum tilts within ± 0.6 deg from its vertical axis as shown in Fig. 8(c) and Fig. 8(d).

5 Conclusion

This work exhibits a procedure to design a controller for a mechanical plant without the necessity for deriving the model differential equations. The mechanical structure has been first developed using SolidWorks platform and then it has been integrated into Simulink environment to obtain the Simscape model of the system. The Simscape model ease the controller design and verification steps. It is also reducing the importance of the physical system existence. A state feedback controller has been proposed, designed, and tuned. Furthermore, the controller performance and robustness have been examined.

The proposed controller effectiveness has been revealed through the simulation results.

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Ahmed Alkamachi was born in Baghdad in 1978. He graduated from the electrical engineering department in University of Baghdad, Iraq, in 2000. He got the MSc degree in electrical engineering/ computer and control division from University of Baghdad, Iraq, 2003. He received the PhD degree in control engineering from Gaziantep University, Turkey, 2017. Since 2004, he has been with Mechatronic engineering department in Al-Khwarizmi college of engineering in University of Baghdad where he is acting as a lecturer. His current research interests span robust control, adaptive control, UAV, and robotics.