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サイバーフィジカルシステムの概念を用いた倒立振子の最適制御スケジューリング

Scheduling to Keep Control Performance by Using Cyber-Physical System

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1. Introduction

In recent years, there is great interest in cyber physical systems that tightly integrate physical systems and information systems from the development of computers and networks [1][2]. However, since the cyber physical system is directly linked with the physical condition, it may cause a big accident when the stops of a takeover and the service occur once [3].

Recently, there are many accident highlighted such as the Maroochy water breach in March 2000 [4], multiple recent power blackouts in Brazil [5], the SQL Slammer worm attack on the Davis Besse nuclear plant in January 2003 [6], the StuxNet computer worm in June 2010 [7], and by various industrial security incidents, cyber physical systems are prone to failures and attacks on their physical infrastructure, and cyber attacks on their data management and communication layer.

Previously cyber attacks were primarily attacks on “information systems,” but in late years came to be turned to “the control system” of large-scale facilities [8][9]. Most of the information in the facility is digitized and stored in the information system. If confidential information leaks from there, it will trigger further attacks. When the information in the facility is clarified, the attacker first falls down the information system, then the control system is targeted and the facilities are damaged. Therefore, it is necessary to construct and operate a secure system in order to operate the cyber physical system.

In the scheduling using the cyber physical system until now, the job scheduler that adjusts the external signal was stopped for the job in which the delay occurred, and only the job without delay was executed. Since the delayed job is stopped for safety, the overall performance will be lower than the original performance. In this research, a job schedule that stabilizes the operation of the system model by performing job scheduling using the concept of the cyber physical system and can operate the attack signal as much as possible against an attack signal such as disturbance is created.

2. Cyber-Physical System

The cyber physical system digitizes a state for the controlled object of the physical world. By quantitatively analyzing the result, we control the object to be controlled object more efficiently.

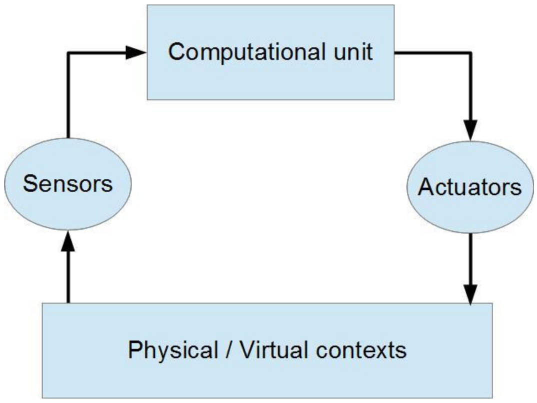

Fig. 1 Basic model

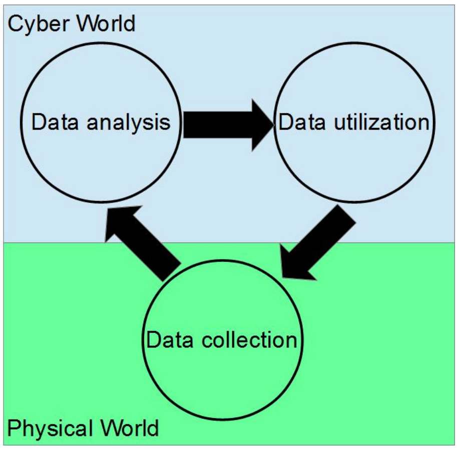

Fig. 2 Relations with the physical world

Specifically, by collecting and using data obtained from the real world, it will contribute to improving the efficiency of the system.

For example, the ITS which is one of transportation system realizes improvement of transportation efficiency and comfort by performing advanced control on the computer based on information on the physical world sent from sensors and cars embedded in roads and signals. The computers are being used to promote efficiency, and attempting to raise production efficiency in agriculture by sprinkling with information obtained from sensors As the system is controlled by the computer, efficiency improvement is promoted and a better society for human beings can be realized

In this research, when the disturbance occurs and it becomes difficult to execute the job, allocate it to the CPU with better performance than the current CPU so that the scheduler sends a scheduling that causes the job to continue so that the concept of the cyber physical system Efficient control is performed by using it. In addition, we propose a job scheduling that can operate without disturbing the system when disturbance occurs by using the theory of cyber physical system as much as possible.

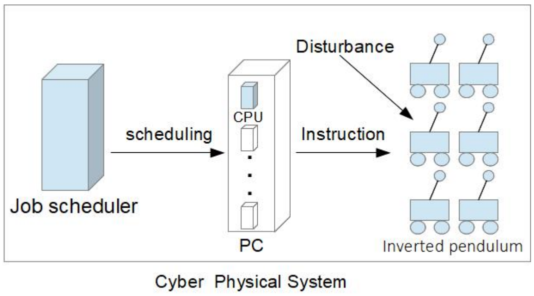

Fig. 3 Full system

3. Experimental Method

3.1 System Model

As an example of linear systems, we will employ the inverted pendulum. This is the most basic experiment of the linear feedback control. Not only we invert a pendulum, but also it is necessary various control which freely move with reversing and wake up from a descent state. In my research, we build a control system by using a state equation to be provided from a inverted pendulum.

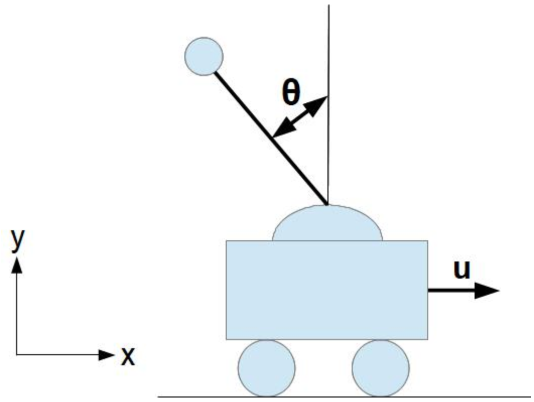

Fig. 4 Inverted pendulum

3.2 Implementation Method

We use the linear quadratic optimal control for the control of the Inverted pendulum. First of all, we define the cost function for the system. When the matrix X satisfies

$$\mu^T X \mu > 0 \quad (1)$$

$$\nu^T X \nu \geqq 0 \quad (2)$$

for arbitrary real vectors μ and ν different from 0. These are called positive definite matrix and positive semi-definite matrix, respectively. The cost function J_d is defined by the following equation:

$$J_d = \sum_{k=0}^{\infty} (\boldsymbol{x}_d(k)^T Q_d \boldsymbol{x}_d(k) + \boldsymbol{u}_d(k)^T R_d \boldsymbol{u}_d(k)), \quad (3)$$

where the matrix Q_d is a semi-definite matrix and the matrix R_d is a positive definite matrix.

It is known that the feedback coefficient matrix of the optimal state feedback $\boldsymbol{u}_d(k) = -F_d \boldsymbol{x}_d(k)$ that minimizes the expression is given by

$$F_d = (R_d + B_d^T P_d B_d)^{-1} B_d^T P_d A_d. \quad (4)$$

Now, P_d is the solution of the Riccati equation of the discrete system:

$$P_d = Q_d + A_d^T P_d A_d - A_d^T P_d B_d (R_d + B_d^T P_d B_d)^{-1} B_d^T P_d A_d. \quad (5)$$

In order to construct feedback that minimizes the equation, it is necessary to solve the discrete Riccati equation. This solution P_d can be calculated as follows. Let $P_d(0)$ be an appropriate positive definite matrix Thereby, when iteratively calculating for each natural number i,

$$P_d(i+1) = Q_d + A_d^T P_d(i) A_d - A_d^T P_d(i) B_d (R_d + B_d^T P_d(i) B_d)^{-1} B_d^T P_d(i) A_d \quad (6)$$

$P_d(\infty)$ converges to the solutionP_d. Therefore, convergence judgment is made appropriately. $P_d(N)$ for sufficiently large N is regarded as solution P_d. Based on the obtained Riccati equation, we stabilize the system.

3.3 Evaluation Value

The input u is created by multiplying the feedback coefficient obtained by the Riccati equation by the position y, speed $\dot{y}$, angle θ, angular velocity $\dot{\theta}$ of the inverted pendulum

Thereby, the evaluation value J can be created from the expression based on position y, speed $\dot{y}$, angle θ, angular velocity $\dot{\theta}$, input u. When creating an inverse pendulum scheduling, refer to the value created based on the evaluation value formula.

$$J = w_1 y^2 + w_2 \dot{y}^2 + w_3 \theta^2 + w_4 \dot{\theta}^2 + r_1 u^2, \quad (7)$$

where w_1, w_2, w_3, w_4,r_1 are positive numbers.

When deciding scheduling to control an inverted pendulum, the previous evaluation value multiplied by 0.9 is added to the scheduling reference value:

$$J[n] = aJ[n-1] + J[n], \ (0 < a < 1). \quad (8)$$

3.4 Scheduling Method

As a scheduling method of my research, we propose a method to change the CPU allocated according to the current evaluation value.

When the evaluation value is high, it is assigned to a CPU with good performance, and when the evaluation value is low, it is assigned to CPU with low performance.

When a disturbance occurs and the evaluation value temporarily rises, it is allocated to the CPU with good performance from the current CPU. As a result, it was made possible to respond when disturbance occurred.

In the following figure, the evaluation value decreases as time elapses, and as a result it is assigned to the one with low CPU performance, but the evaluation value rises as disturbance occurs 3 seconds later.

If you use a CPU with low performance without scheduling, It is impossible to continue execution of the job. However, by using the concept of cyber physical system and performing scheduling by the evaluation value obtained from the current inverted pendulum, it can be allocated to an appropriate CPU.

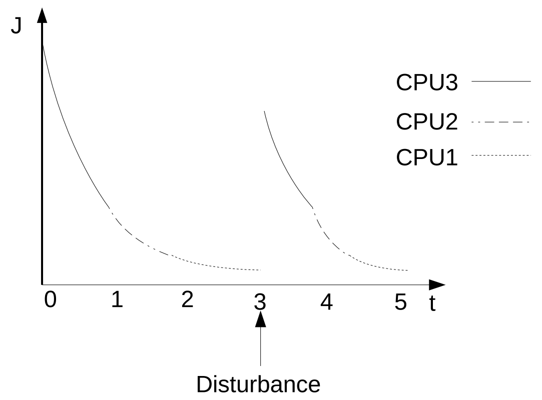

Fig. 5 Scheduling method

4. Experimental Result

The program assumes that 1000 inverted pendulums are controlled by 8 CPUs and the sampling period is 0.01 second, 0.02 second, 0.04 second, 0.08 second, 0.16 second, 0.32 second, 0.64 second, 1.00 second.

During execution of the program, scheduling is performed based on the evaluation value, and when the evaluation value is high, it is assigned to a CPU with good performance, and when the evaluation value is low, it is assigned to CPU with poor performance.

We set the disturbance to be applied to the inverted pendulum at a specific time so that we can continue execution of the job by carrying out appropriate scheduling even when the disturbance is applied and the value of the evaluation value rises.

Specifically, disturbance of setting was applied such that a force of about 11degree is applied for only a moment in the positive direction 3 seconds after the angle of the inverted pendulum.

In Figs.6 and 7, control is performed with a CPU with a sampling period of 1.00sec, Fig.6 is an evaluation value when no disturbance is applied, and Fig.7 is an evaluation value when a disturbance is applied at a specific time.

If the disturbance is not applied, execution of the job can be continued, but if a little disturbance is applied, the job can not be executed.

So in Fig.8, when disturbance is applied, job execution can be continued by shifting to the CPU determined by scheduling.

In Fig.8, the sampling period is from 0.01 to 0.02 for CPU 3, the sampling period from 0.04sec to 0.16sec for CPU 2, and the sampling period from 0.32sec to 0.1sec for CPU 1.

The execution result of the program is as follows. All inverted pendulums are not displayed and only 12 are displayed, and the simulation time is done in 10sec, and the evaluation values obtained from the inverted pendulum at that time are as follows.

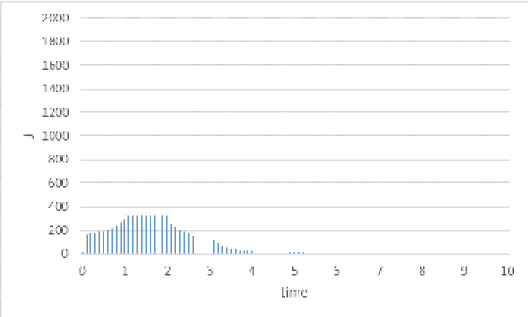

Fig. 6　Evaluation value without disturbance

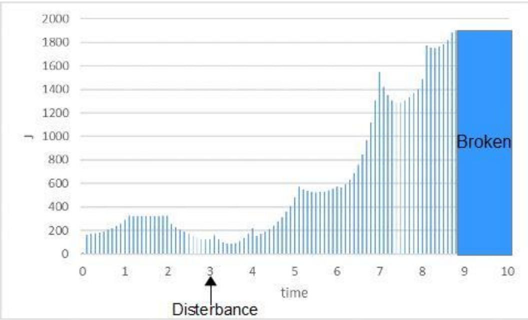

Fig. 7　Evaluation value with disturbance

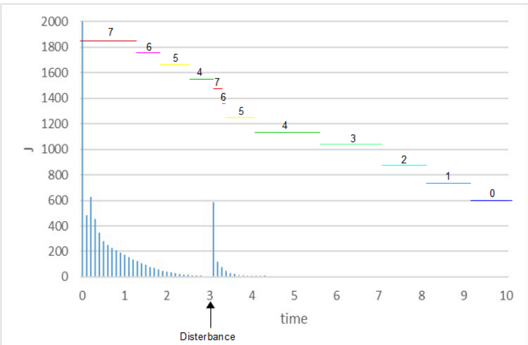

Fig. 8　Evaluation value with scheduling

5. Conclusion

In this experiment we successfully stabilized the inverted pendulum using the parameters obtained from the Riccati equation and the scheduling considered. By using the concept of cyber physical system we could observe the state of inverted pendulum and could create evaluation value. Furthermore, it was able to cope with the occurrence of disturbance by the scheduling based on the evaluation value, so it was possible to increase the strength of the system. However, since individual attacks are not taken into consideration, future research should consider scheduling in the state including them.

参考文献

1) 吉本達也, 潮俊光, “サイバーフィジカルシステムにおける制御性能の最適化のためのジョブスキッピング,” 電子情報通信学会技術研究報告 VLD, VLSI 設計技術, **110**(87), pp.53–58, 2010-06-14.

2) 岩野 和生, 高島 洋典, “サイバーフィジカルシステムと IoT(モノのインターネット),” 情報管理, **57**(11), pp.826–834, 2015.

3) F. Pasqualetti, “Attack Detection and Identification in Cyber-Physical Systems”, *IEEE Trans. Automatic Control*, **AC-58**(11), pp.2715–2729, 2013.

4) J. Slay and M. Miller, “Lessons learned from the Maroochy water breach,” Critical Infrastructure Protection, **253**, pp.73–82, 2007.

5) J. P. Conti, “The day the samba stopped,” *Engineering & Technology*, **5**(4), pp.46–47, 2010.

6) S. Kuvshinkova, “SQL Slammer worm lessons learned for consideration by the electricity sector,” North American Electric Reliability Council, 2003.

7) J. P. Farwell and R. Rohozinski, “Stuxnet and the future of cyber war,” *Survival*, **53**(1), pp.23–40, 2011.

8) F. Zhang, K. Szwaykowska, W. Wolf, and Vincent Mooney, “Task Scheduling for Control Oriented Requirements for Cyber-Physical Systems,” *Proceedings of 2008 Real-Time Systems Symposium*, pp.47–56, 2008.

9) 岩野 和生他, “CPS(Cyber Physical Systems) 基盤技術の研究開発とその社会への導入に関する提案 —高齢者の社会参加促進を事例として—”, 科学技術振興機構, **CDS-FY2012-SP-05**, 2013.

10) サイバーとフィジカル NEC ならではのセキュリティ技術で、社会をより安全・安心に, SECURITY SHOW 2017 レポート, 2017.

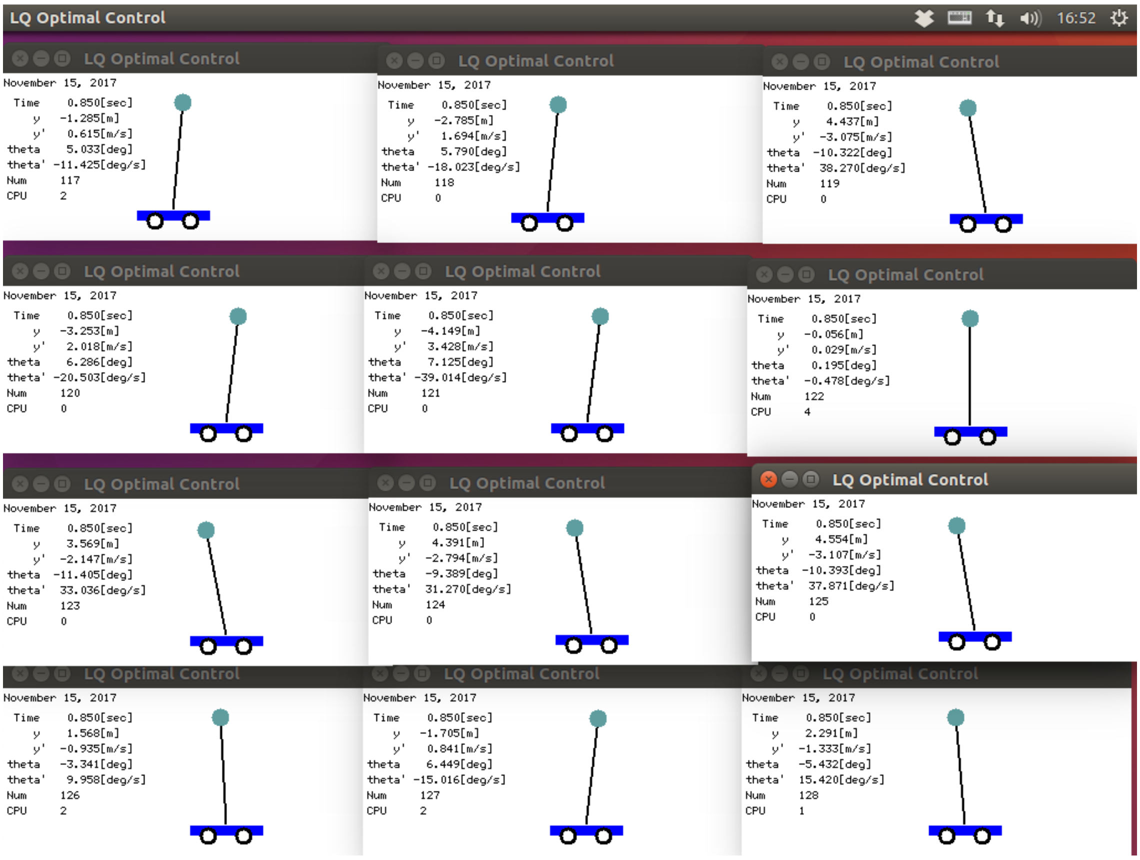

Fig. 9 Execution result