ENOC-2008, Saint Petersburg, Russia, June, 30–July, 4 2008

MULTIPENDULUM MECHATRONIC SETUP FOR STUDYING CONTROL AND SYNCHRONIZATION

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Abstract

In the paper a novel multipendulum mechatronic setup is described. It allows to implement different algorithms of estimation, synchronization and control. The set-up is aimed at solving various research and educational tasks in the areas of hybrid modeling, analysis, identification and control of mechanical systems.

Key words

Nonlinear dynamics, Communication constraints, Mechatronic set-up

1 Introduction

Problems of oscillatory mechanical systems control and synchronization have significant theoretical interest and practical value. For the purposes of research and control engineering education it is important to build up appropriate laboratory equipment and software to work for investigation of this kind of system. There are many papers where this problem was considered and significant results have been achieved (Christini *et al.*, 1996; Blekhman *et al.*, 1997; Andrievsky *et al.*, 1998; Fradkov, 1999; Åström and Furuta, 2000; Andrievsky and Boykov, 2001; Blekhman and Fradkov, 2001; Kumon *et al.*, 2002; Santoboni *et al.*, 2003; Fradkov *et al.*, 2005; Fradkov, 2005; Fradkov, 2007). In the last decades various mechatronic laboratory setups have been described in the literature: inverted pendulum (Furuta and Yamakita, 1991), Schmid pendulum (a reaction-wheel pendulum) (Schmid, 1999; Spong *et al.*, 2001; Andrievsky, 2004), cart-pendulum (Gromov and Raisch, 2003; Gawthrop and McGookin, 2004; Graichen *et al.*, 2007), Furuta pendulum (Furuta *et al.*, 1994; Åström and Furuta, 2000; Suzuki *et al.*, 2004*a*; Suzuki *et al.*, 2004*b*), coupled two-pendulum systems (Andrievsky and Boykov, 2001; Kumon *et al.*, 2002; Fradkov *et al.*, 2002; Fradkov *et al.*, 2005; Yagasaki, 2007), pendubot (Spong and Block, 1996), humanoid robots (Kim and Oh, 2004), crane systems (Masoud *et al.*, 2004; Wollherr and Buss, 2003), pendulum-like juggling system (Suzuki *et al.*, 2003), force feedback paddle (Saigo *et al.*, 2003), laboratory model helicopters (Apkarian, 1999; Andrievsky *et al.*, 2007), etc. The usage of such equipment is threefold. Firstly, such units are useful for research since they may serve as testbeds for testing new control algorithms under real world constraints. Secondly, it is used for education, allowing students to enhance their skills in control systems design. Finally, it may be used for demonstration, attracting newcomers to the control systems area.

In the present paper the multipendulum mechatronic setup, designed in the Institute for Problems of Mechanical Engineering of RAS (Saint Petersburg, Russia) in the framework of the Russia–Netherlands cooperation program.

The multipendulum mechatronic setup of IPME RAS includes:

– a modular multi-section mechanical oscillating system;
– an electrical equipment (with computer interface facilities);
– the personal computer for experimental data processing, representation of the results the real-time control.

For data exchange via standard In-Out ports of the computer, the special exchange routine is written. The devices are connected by means of the elastic link. In Sec. 2 a brief description of the construction is presented. For making laboratory experiments and on-line control, electrical design, data exchange interface and software tools were created. Their description is given in Sec. 3.

2 Design of mechanical part

The setup consists of a number of identical pendulum sections connected with springs. The schematics of a pendulum section is presented in Fig. 1, while a photo of four sections is given in Fig. 2. The foundation of the section is a hollow rectangular body. Inside the body an electrical magnet and electronic controller board are mounted. On the foundation the figure support containing the platform for placing the sensors in its middle part is mounted. The pendulum itself possesses a permanent magnet tip in the bottom part. The working ends of the permanent magnet and the electrical magnet are posed exactly opposite each other and separated with a non-magnetic plate in a window of the body. The idea behind control of the pendulum is changing the poles of the electrical magnet by means of switching the direction of the current in the windings of the electrical magnet. In order to allow changing the eigenfrequency of the pendulum oscillations the pendulum is endowed with additional plummets and counterparts changing its effective length (the distance between the suspension point and the center of mass. On the rotation axis of the pendulum the optical encoder disk for measuring the angle (phase) of the pendulum is mounted. It has 90 slits. The peripheral part of the disk is posed into the slit of the sensor support. The sensor consists of a radiator (emitting diode) and a receiver (photodiode). The obtained sequences of signals allow to measure angle (phase) and angular velocity of the pendulum, evaluate amplitude and crossing times and other variables related to the pendulum dynamics.

Axes of the neighbor sections are connected with the torsion springs, arranging force interaction and allowing exchanging energy between neighbor sections. The set of interconnected pendulum sections represents a complex oscillatory dynamical system, characterized by nonlinearity and high number of degrees of freedom. Such a mechanical system can serve as a basis for numerous educational and research experiments related to dynamics, control and synchronization in the networks of multidimensional nonlinear dynamical systems. In principle, any number of sections can be connected. At the moment mechanical parts of 50 sections are manufactured.

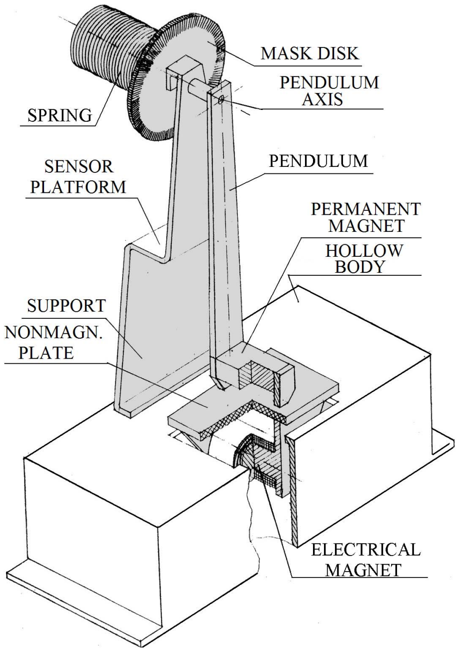

Figure 1. Schematics of the pendulum section.

Figure 2. Photo of four coupled pendulum sections.

3 Electronics of the multipendulum setup

Oscillation control is provided on the basis of combined hardware/software method. The energy for excitation is transmitted by the pulse-width modulated (PWM) signal with the constant level and variable duty cycle. From the programming point of view, hardware is represented by the write-only registers (WO) for putting in the prescribed duty cycle of control signal from the computer, and the read-only registers (RO) for transfer oscillation halfperiod duration values to the computer. The PWM based method provides more precise control than the number-pulse one, because of averaging the high frequency pulses by the mechanical subsystem. The *control unit* generates the exciting action applied to the pendulums via the opposite magnetic fields. It includes bi-channel *asynchronous pulse-width modulator* (APWM), the Data Exchange System and the power amplifiers to drive the electromagnets.

3.1 System for data exchange with control computer

The Data Exchange System of the setup is intended to transfer data and control commands from the Control Computer to the interface board of the pendulum sections. Each interface board is an intelligent measuring/controlling electronic devise, assigned for unloading processor of the Control Computer from chores of forming the control signal and preventing the Control Computer from a wasteful wait state of the sensor replies.

A main problem for designing the Data Exchange System was a demand to increase the channel capacity, preventing, at the same time, any loss of synchronism in interaction between the Control Computer and the pendulum sections. Since the setup consists of a large number (up to 50) pendulum sections, and the number of enabled sections may be different for different experiments, and also the sections arrangement may be modified, designing of data exchange interface is a hard problem. Demand of hardware independence and universality of the data exchange interface should be also taken into account since it makes possible ensuring compatibility of the stand with standard PCs and the microcontroller-based information processing systems as well.

3.2 Architecture of the Data Exchange System

The most reasonable architecture for the Information Management Systems, including $5 - 8$ assemblies and more is a *data-bus* one. The bus of the multipendulum setup works in a *bidirectional* mode. It consists of:

- the bidirectional data link;
- the control lines;
- the confirmation line;
- the power supply lines.

Hardwired noise immunity is ensured by terminating resistors insertion to the both end of the bus. To prevent the bus-conflict accidents, caused by faults of the setup units, the open collector (open-drain) transmitters and inverting receivers are exploited in the data-bus design. Using this technology makes it possible to restrict an abnormal current for each single bus line choosing resistance of the terminating resistor. A total length of the data bus is 14 m.

3.3 Computer-process interface

Different types of interface, applicable both for PCs and special-purpose hardware, such as a serial port (USART and USB); parallel port (SPP, ECP, EPP), the Fast Ethernet channel, IEEE1394 interface, and the IDE channel were analyzed. The main requirements to the interface are as follows:

- ability of the direct access to registers;
- byte-wide or word-wide mode of operation;
- high carrying capacity (no less than 1 MB/s);
- data-bus architecture capability.

The EPP (Enhanced Parallel Port) was chosen as the most efficient interface, allowing to organize synchronous data exchange and a data-bus architecture of the communication link. For matching the data bus and the standard parallel port of the PC, an add-on device, the *dispatcher* was designed. The dispatcher is intended for:

- inversion of received and transmitted data;
- front-side bus signal generation;
- generation of waiting intervals in the absence of the bus response;
- generation of the “error” reply in the absence of the bus response during the waiting interval;
- processing of the EPP data communications protocol for the data exchange with PC, complying with the IEEE1284 standard.

3.4 Electronic modules of the set-up

Pendulum sections and electric motors are equipped with the electronic modules. The electronic modules have following functions:

- data exchange with the data bus;
- generation of control signals for executive devices (the pendulum actuating coils and the electric motors);
- processing of the sensor signals

Control of pendulums is performed by pulse-width modulation (PWM) of the electric voltage applied to the actuating coil of the electric magnet mounted in the basement of the pendulum section (see Fig. 1). The magnetic field strength is a rapidly decreasing function of a distance between the electric magnet and the pendulum bob. Therefore in the self-directed mode the control voltages are automatically applied to the actuating coil when the pendulum bob is in the vicinity of its lower position. The measured quantities of each pendulum section are the *angular displacement* and the *driving direction* of the bob. The angular encoder, mounted in alignment with the pendulum axis, is used as a sensor. Pulse patterns from the encoder outputs are transformed by the logical units of the electronic modules into binary codes, which may be read out under data bus requests.

Control of the electric motors is implemented by applying the pulse-width modulated voltage to the armature coil. For changing the direction of the motor driving torque, the double-channel PW modulators and the bridge power amplification circuits are used in the output stages of motor control.

The electronic modules of the dispatcher, of the pendulum sections and motors control are designed based on single-type solutions employing the *All-in-One Logical Cards* (AOLCs). The kernel component of AOLC is Field Programmable Gate Array chip EPM240T100C5 with the logical capacity in 240 macrocells, manufactured by *Altera* Co. Logic synthesis was made with the help of *Quartus II Design Software*, ver 5.1. The chip resources are used up to 80% of the full capacity.

The machine code of the electronic modules includes: write instruction for controlling parameters; read instruction for measured data; executive instruction for switching the module mode (self-acting or software-based modes).

3.5 Communications protocol

The communications protocol secures writing the instructions and command qualifiers to the interface board of the pendulum sections and reading the data, measured by the interface board sensors. The communications protocol uses three kinds of passing: address passing, instruction (mode) passing and data passing. The communications protocol is based on explicit addressing with use of Enhanced Parallel Port (EPP) registers of the PC in accordance with the IEEE 1284

Parallel Port Standard: address register = (base address+3), data register = (base address+4). The registers are available for read-write operations.

For transfer modes ensuring the address register of the EPP-port is used. For logical separation of the data and instruction flows is made by means of two high stages of the address register. The rest five stages of this register contain the module address for access on the next R/W cycle.

Described data exchange protocol ensures exchange rate up to 9615 Hz for simultaneous operation over the bus with all 52 modules and up to 500 kHz for operation with a single module (delays for data processing in PC are not taken into account in the above estimate).

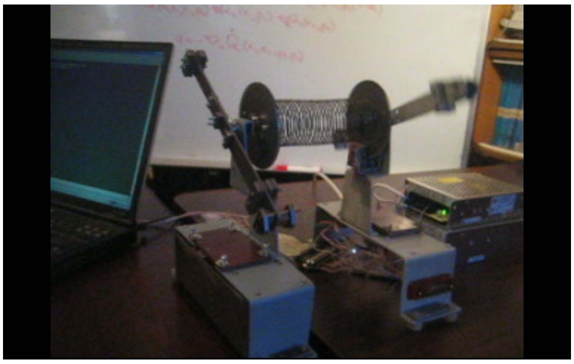

Figure 3. Inphase synchronization of the coupled active and passive pendulums.

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Figure 4. Antiphase synchronization of the coupled active and passive pendulums.

Conclusions

The system is currently being tested and tuned. Four active and up to 46 passive sections are ready for connection. Already at this stage the system can be used for demonstration and for research. Connecting one active and two passive sections one can demonstrate either inphase and antiphase synchronization of the active and passive pendulums, see Figs. 3, 4. The experiments show that the type of the synchronization mode (inphase or antiphase) depends on the initial conditions that agree with the conclusions of (Fradkov and Andrievsky, 2007).

Some new features of the set-up were discovered during first experiments. For example it appears that it is easy to change the stiffness characteristics of the spring by means of changing distance between the sections. Increasing spring stiffness allows expanding the regions of attraction of the stable synchronous mode.

Acknowledgements

The work was supported by the Russian Foundation for Basic Research (projects RFBR 06-08-01386, 08-01-00775), the Russia–Netherlands cooperation program (project NWO–RFBR 047.011.2004.004) and the Council for grants of the RF President to support young Russian researchers and leading scientific schools (project NSh-2387.2008.1).

References

Andrievsky, B., D. Peaucelle and A. L. Fradkov (2007). Adaptive control of 3DOF motion for LAAS Helicopter Benchmark: Design and experiments. In: *Proc. 2007 Amer. Control Conf*. New York, USA. pp. 3312–3317.

Andrievsky, B. R. (2004). Stabilization of the inverted reaction wheel pendulum. In: *Control in Physical and Technical Systems* (A. L. Fradkov, Ed.). pp. 52–71. Nauka. St. Petersburg. (in Russian).

Andrievsky, B. R., A. L. Fradkov, V. A. Konoplev and A. P. Konjukhov (1998). Control, state estimation and laboratory experiments with oscillatory mechanical system. In: *Prepr. Nonlinear Control Design Symposium NOLCOS98*. Twente, Holland. pp. 761–764.

Andrievsky, B. R. and K. B. Boykov (2001). Numerical and laboratory experiments with controlled coupled pendulums. In: *Prepr. Nonlinear Control Design Symposium NOLCOS'01*. St. Petersburg, Russia. pp. 824–829.

Apkarian, J. (1999). Internet control. Circuit Cellar. http://www.circuitcellar.com.

Åström, K.J. and K. Furuta (2000). Swinging up a pendulum by energy control. *Automatica* **36**(2), 287–295.

Blekhman, I. I., A. L. Fradkov, H. Nijmeijer and A. Y. Pogromsky (1997). On self-synchronization and controlled synchronization of dynamical systems. *Systems & Control Letters* **31**(5), 299–306.

Blekhman, I. I. and Fradkov, A. L., Eds.) (2001). *Control of Mechatronic Vibrational Units*. Nauka. St.Petersburg. in Russian.

Christini, D. J., J. J. Collins and P. S. Linsay (1996). Experimental control of highdimensional chaos: The driven double pendulum. *Phys. Rev. E*.

Fradkov, A. L. (1999). Exploring nonlinearity by feedback. *Physica D*. **128**(2–4), 159–168.

Fradkov, A. L. (2005). Application of cybernetical methods in physics. *Physics–Uspekhi* **48**(2), 103–127.

Fradkov, A. L. (2007). *Cybernetical Physics: From*

Control of Chaos to Quantum Control. Springer-Verlag. Berlin-Heiderlberg.

Fradkov, A. L. and B. Andrievsky (2007). Synchronization and phase relations in the motion of two-pendulum system. *Int. J. Non-Linear Mechanics* **42**(6), 895–901.

Fradkov, A. L., B. R. Andrievsky and K. B. Boykov (2002). Numerical and experimental excitability analysis of multi-pendulum mechatronics system. In: *Proc. 15th IFAC World Congress*. Barcelona, Spain.

Fradkov, A. L., B. R. Andrievsky and K. B. Boykov (2005). Control of the coupled double pendulums system. *Mechatronics* **15**, 1289–1303.

Furuta, K. and M. Yamakita (1991). Swing up control of inverted pendulum. In: *Proc. IECON91*. pp. 2193–2198.

Furuta, K., M. Yamakita, S. Kobayasji and M. Nishimura (1994). A new inverted pendulum apparatus for education. In: *Proc. IFAC Symp. on Advances Contr. Education*. Tokyo. pp. 191–194.

Gawthrop, P. J. and E. McGookin (2004). A LEGO-based control experiment. *IEEE Control Syst. Mag.* **24**(5), 43–56.

Graichen, K., M. Treuer and M. Zeitz (2007). Swing-up of the double pendulum on a cart by feedforward and feedback control with experimental validation. *Automatica* **43**(1), 63–71.

Gromov, D. and J. Raisch (2003). Hybrid control of a cart-pendulum system with restrictions on the travel. In: *Proc. Int. Conf. Physics and Control*. Vol. 4. St. Petersburg, Russia. pp. 1231–1235.

Kim, J. H. and J. H. Oh (2004). Realization of dynamic walking for the humanoid robot platform KHR-1. *Adv. Robot.* **18**(7), 749–768.

Kumon, M., R. Washizaki, J. Sato, R. Kohzawaa nd I. Mizumoto and Z. Iwai (2002). Controlled synchronization of two 1-DOF coupled oscillators. In: *Proc. 15th Triennial World Congress of IFAC*. Barcelona, Spain.

Masoud, Z. N., A. H. Nayfeh and D. T. Mook (2004). Cargo pendulation reduction of ship-mounted cranes. *Nonlinear Dyn.* **35**(3), 299–311.

Saigo, M., K. Tani and H. Usui (2003). Vibration control of a traveling suspended system using wave absorbing control. *Vib. Acoust.-Trans. ASME* **125**(3), 343–350.

Santoboni, G., A. Yu. Pogromsky and H. Nijmeijer (2003). Application of partial observability for analysis and design of synchronized systems. *Chaos, Solitons and Fractals* **13**(1), 356–363.

Schmid, Chr. (1999). An autonomous self-rising pendulum. Invited paper. In: *Proc. European Control Conference ECC'99*. Karlsruhe.

Spong, M. W. and D. Block (1996). The Pendubot: A mechatronic systems for control research and education. In: *Proc. 35th IEEE Conf. Dec. Control (CDC'96)*. New Orleans, USA. pp. 555–556.

Spong, M. W., P. Corke and R. Lozano (2001). Nonlinear control of the Reaction Wheel Pendulum. *Automatica* **37**, 1845–1851.

Suzuki, S., K. Furuta, A. Sugiki and S. Hatakeyama (2004*a*). Nonlinear optimal internal forces control and application to swing-up and stabilization of pendulum. *Dyn. Syst. Meas. Control-Trans. ASME* **126**(3), 568–573.

Suzuki, S., K. Furuta and S. Shiratori (2003). Adaptive impact shot control by pendulum-like juggling system. *Int. J. Ser. C-Mech. Syst. Mach. Elem. Manuf.* **46**(3), 973–981.

Suzuki, S., Y. Pan, K. Furuta and S. Hatakeyama (2004*b*). VS-control with time-varying sliding sector – Design and application to pendulum. *Asian J. Control* **6**(3), 307–316.

Wollherr, D. and M. Buss (2003). Cost-oriented virtual reality and real-time control system architecture Robotica. **21**(3), 289–294.

Yagasaki, K. (2007). Extension of a chaos control method to unstable trajectories on infinite - or finite-time intervals: Experimental verification. *Phys. Lett. A* **368**(3,4), 222–226.