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Implementation of Smoothing Filtering Methods for the Purpose of Improvement Inverted Pendulum's Trajectory

Abstract. *In this paper various smoothing filters were applied in order to smooth inverted pendulum's movement trajectory. The filtering was implemented for the purpose of some artifacts removal. The authors tested various classical smoothing filters on the single-inverted pendulum, which is a classical problem in control theory and is widely used for the purpose for testing various control algorithms, neural networks, fuzzy control, genetic algorithms etc. . .*

Streszczenie. *W niniejszym artykule zastosowano filtry wygładzające w celu wygładzenia trajektorii ruchu odwróconego wahadła. Filtracja została użyta do usunięcia zakłóceń . Autorzy przetestowali różne klasyczne filtry wygładzające na wahadle odwróconym, który jest klasycznym problemem w teorii sterowania i ma szerokie zastosowanie do testów różnych algorytmów, sieci neuronowych, w logice rozmytej, algorytmach genetycznych itp.* ***(Zastosowanie metod opartych o filtry wygładzające w celu poprawy trajektorii ruchu wahadła 0dwróconego)***

Keywords: Inverted pendulum, control, filtering
Słowa kluczowe: Odwrócone wahadło, sterowanie, filtracja

Introduction

The inverted pendulum is a classical problem in dynamics and control theory and is widely used as a reference for testing control algorithms (PID-controllers, neural networks, fuzzy control, genetic algorithms, etc .). There are many methods that allow control over an inverted pendulum, such as classical control methods and methods based on the application of machine learning theory. Rocket control systems, robotics, construction cranes are the main areas of application of these methods, but they are most used in stabilizing cranes in a shipyard [2, 3].

The inverted pendulum system has two types of equilibria, one of which is stable and the other unstable. Stable equilibrium refers to a state similar to a pendulum suspended down. In the absence of any holding force, this system will return to its original state. Stable equilibrium does not require control and therefore is a simpler task from a management point of view. Unstable equilibrium corresponds to the state in which the pendulum is located strictly at the top, requiring some force to maintain this position [3]. The system of the inverse pendulum (fixed, for example, on the motor shaft) can be applied in robotics when moving humanoid robots. With the help of engines, the angle of position of the component parts of the robot is changed, which makes it possible to maintain its equilibrium point and prevents the robot from falling. Also, this system is used to stabilize the position of rocket launcher [3, 4].

The inverted pendulum is one of the most popular nonlinear systems applied mainly for testing purposes in research and education. The system is non-linear mostly due to inter alia gravitational effects. Another aspect of using inverted pendulum is strongly related with the problem of its position's stabilization and balancing of the pendulum during swinging up [13].

This paper is mostly concentrated on implementation of the smooth filters for the purpose of disturbances removal in pendulum's trajectory. The study is at initial stage thus only basic inverted pendulum was applied. The author's of the hereof paper are currently working on application of the proposed solution for double- and triple-inverted pendulums. It is also planned to implement fractional filters, which have some smoothing features.

The definition of filter usually is related with a system or device able to transfer in accordance with some specific rules input into desired output. To simplify this term – filters are applied to keep all frequency components which belong to particular frequency rangeand reject those undesired. It is possible to differentiate linear and non-linear filtes [1, 14].

It is also possible to define filters as simple mathematical operators applied for signals' analysis. The most popular filters are FIR (Finite Impulse Response), IIR (Infinite Impulse Response) and notch. It is possible to divide them into upper-, lower- and band-pass [5, 6, 7].

Smoothing Filters

Smoothing filters are becoming more and more popular in various research areas due to its ability for extraction more desired data form analysed signals. During smoothing, the signal data points are modified in a way where inter alia noises are reduced, and points that are lower than neighboring points are increased, which leads to a smoother signal
[15, 17, 18]

Smoothing filters (such as Medfilter or Savitzky-Golay Filter) are different from other filters in that they limit the risk of data cutouts that will be needed and as a result – the smoothed values can be written as a linear transformation of the values, the smoothing operation is known as a linear smoother [21, 20].

Non-linear filters differ from linear filters, in that they are adaptive, in practice this means that they retain the so-called
edges [14, 15, 17, 18, 19].

Trajectory lines in inverted pendulums are spiky and therefore require smoothing and therefore the authors of this paper decided to apply smotthing filters such as Savitzky-Golay and Median Filters, where the remaining spikes are corrected [21, 20]. The Savitzky-Golay Filter is a least square smoothing filter, it is also knows as a digital polynomial filter. It substitutes each value with a new value, previously obtained from a polynomial fitting, which is performed with a basic linear least square fitting to the 2n+1 neighboring points, where the value n could be equal or greater then the order of the applied polynomial. The more neighbors are applied – the smoother will be the final signal [20].

Inverted Pendulum

The inverted pendulum has been studied for decades and seems to be very thoroughly researched. This is because it revealed a number of dynamic phenomena especially in area of stabilisation of unstable equilibrium position. It is also one of the most versatile and popular non-linear system [12].

As a self-balancing system – the inverted pendulum has become a subject of growing interest in theory and practical applications for decades Inverted pendulums can be developed in rotary, on cart or as a wheel system. The analysis of its robustness is usually evaluated in order to check how fast its stability could be achieved [11].

Under-actuated systems and their control have been a challenging problem especially because of some associated with it restrictions of the non actuated variables. As it was mentioned already before – such systems have been very thoroughly examined but their exact control remain a problem. The inverted pendulum as one of the most popular nonlinear under actuated systems is till now used in linear and non-linear control as a benchmark sample. The system is highly non-linear mainly because the gravitational effects and centripetal forces and in certain configurations it may lack stability. To such becomes problem with balancing of the vertical pendulum in its upper position and the overall stabilization around this position[13].

One of the main goals of this study is filtering of the inverted pendulum's trajectory in order to improve its stability. Some studied applied inter alia Kalman filters in order to cope with inter alia quantization noise, which has a very bad influence on state space controller [9].

The single-inverted pendulum (LQR – Linear Quadratic Regulator) is a very basic system unlike the double-inverted pendulum – one of the most popular systems applied in mechatronics for the purpose of control and estimation strategies study [8, 9].

Research Methodology

The Savitzky-Golay filter is a digital filter used in order to smooth the curves and as a result to increase the signal noise ratio (SNR) without significant distortion of the analysed data [10, 21]. The median filter is a non-linear filter, where the mean value of a sequence of values in the ascending order of data of the processed point and its surroundings is measured. The advantage of this filter is that all of the values that deviate from the average are omitted [10].

For this study purposes the authors applied Savitzky-Golay filter with the following parameters: 19 (order) and 211 (frame length) and the Median Filter of the 30-th order. The results were satisfying. As mentioned above – Savitzky- Golay is a digital polynomial filter (or a least smoothing filter) [20]. Both filters are smoothing filters [16, 21, 22].

Experimental Environment

In ideal, perfect, impossible case is where there is no noise interference. Real life however gives some difficulties. For the study purpose the outhors used single-inverted pendulum (see: Fig. 1 and Fig. 2), which consists of inverter line, actuator (DC motor) with incremental sensor, pendulum arm with incremental sensor. The model (Fig. 1) consists of:

- $x_1; x_2$ – angle, angular velocity of the arm;
- $x_3; x_4$ – position, carriage speed;
- u – truck's acceleration;
- $g; l; b$ – parameters (gravity acceleration, distance $|MP|$, friction coefficient).

Two-Degrees Control Structure (2-DOF) (Fig. 3):

- **x***(t) – reference trajectory;
- u*(t) – reference control;
- **K**(t) – state controller.

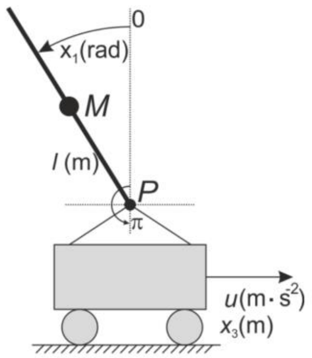

Fig. 1. Simplified scheme of applied inverted pendulum

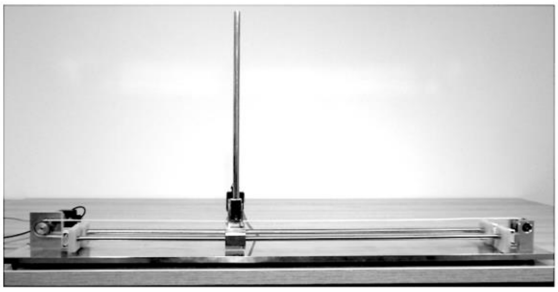

Fig. 2. Implemented device.

Results and Conclusions

In perfect, ideal case – there is no noise reference. Everything looks smooth. This is why models so frequently differ from reality [8]. Stabilisation's approaches of such systems have been carried for decades [11]. The data presented in Figures 4 – 6 (x2 and x4) was a real data, coming from real inverted pendulum. Basic, median filter proved to be more efficient then Savizky-Golay filter.

It is visible, that some trajectories' smoothing and filtering was needed, however while the results from the data x_2 were very promising – while the same filters applied on x_4 gave different results (please see: Figures: 9 and 10). Further investigation is currently conducted by the authors of this paper.

Simulation is always different from the reality, no matter how hard we try to make is as close to it as possible. Data x_1 and x_3 were simulated. It is easy to observe that there is no interference in the simulated pendulum's trajectory (see: Fig. 7 and 8). Therefore adding extra filtering had no point, but was performed. Further tests are being in progress, especially in real-life conditions, where real signals were applied.

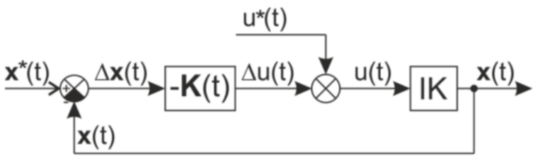

Fig. 3. Two-Degrees Control Structure – scheme.

The study is still at initial stage as the authors of this paper for tests purposes only decided to apply basic inverted pendulum. The authors are currently working on application of the proposed filtering for double- and triple-inverted pendulums. It is also planned to implement fractional filters, which also have some smoothing features.

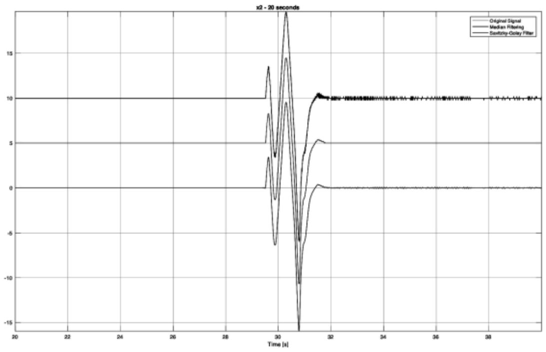

Fig. 4. x_2 – real signal, 20 seconds

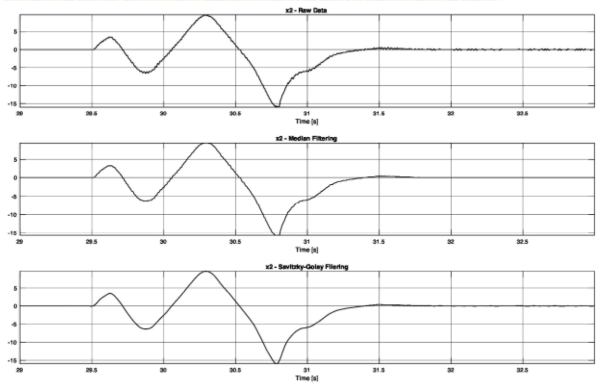

Fig. 5. x_2 – real signal, 4 seconds

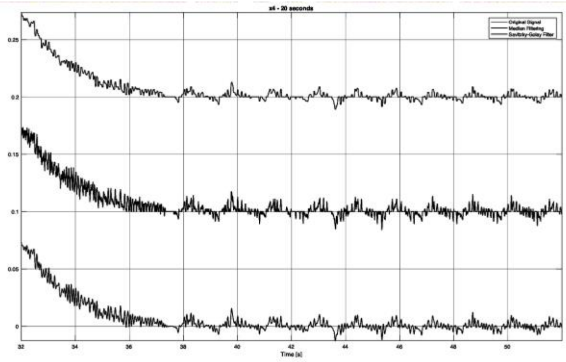

Fig. 6. x_4 – real signal, 20 seconds

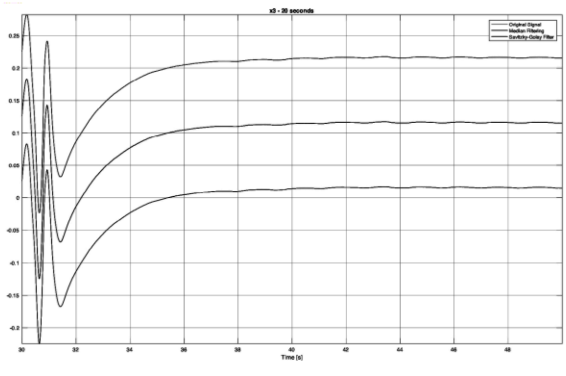

Fig. 7. x_3 – simulated signal, 20 seconds

Why the next step involves double-inverted pendulum? Because it is the one of the most popular mechatronic systems and is successfully applied for control and estimation strategies. Dynamics of such pendulum is complex and provides provides a system perfect for design and development of new control methodologies [8]. It could be successfully applied for various importnt areas such as holding a balnace of a robot or to design more stable walking robot [8, 11].

Further research plan include also tests on tripleinverted pendulums.

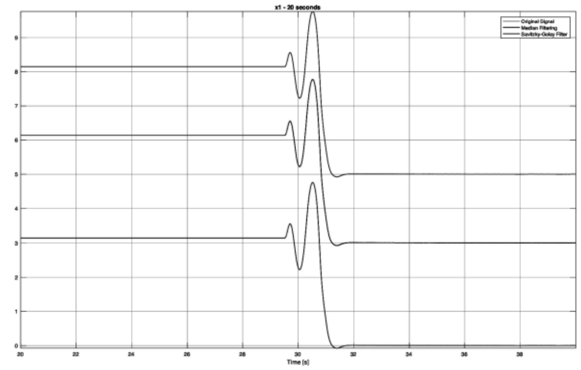

Fig. 8. x_1 – simulated signal, 20 seconds

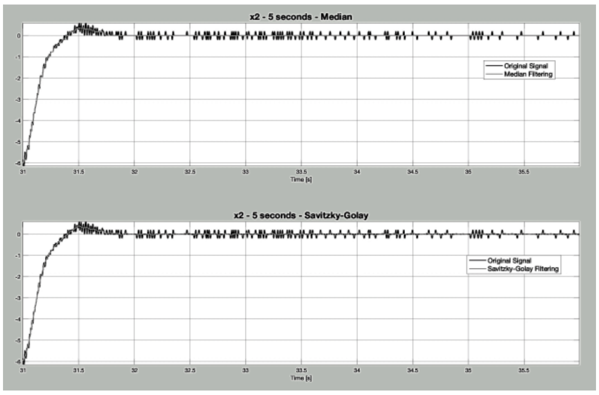

Fig. 9. x_2 – real signal, 5 seconds – filters' comparison

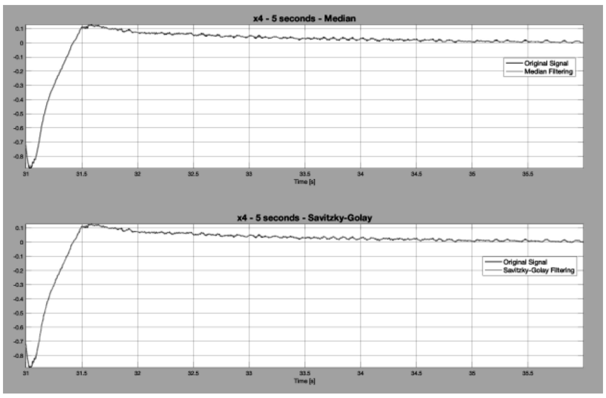

Fig. 10. x_4 – real signal, 5 seconds – filters' comparison

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REFERENCES

[1] Farhang-Boroujeny B.: Adaptive Filters: Theory and Applications, John Wiley and Sons, 2013.
[2] McC. Siebert W.: Circuits, Signals, and Systems, MIT Press, 1986.
[3] Druzhinina O. V.: Modelirovanie i postroenie algoritma stabilizacii perevernutogo majatnika, Dinamika slozhnyh sistem - XXI vek, 4, 2012 (in Russian).
[4] Bobobekov K. M.: The Model of the Inverted Pendulum: Special Cases, Collection of Scientific Works of the Novosibirsk State Technical University, 3(81), pp. 21-42, Novosibirsk State Technical University, 2015 (in Russian).
[5] da Costa V. L. R., Schettino H. V., Camponogara A., de Campos F. P., Ribeiro M. V.: Digital Filters for Clustered-OFDMbased PLC Systems: Design and Implementation, Digital Signal Processing, 70, pp. 166-177, 2017.
[6] Tibdewal M. N., Mahadevappa M., Kumar Ray A., Malokar M., Dey H. R.: Power Line and Ocular Artifact Denoising from EEG Using Notch Filter and Wavelet Transform In Proc.: 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), pp. 1654-1659, IEEE, 2016.
[7] Diniz P. S., Da Silva E. A., Netto S. L.: Digital Signal Processing: System Analysis and Design, Cambridge University Press, 2010.
[8] Xu B., Lyu Y., Gadsden S. A.: Estimation And Control Of A Double-Inverted Pendulum, 2018.
[9] Kloppelt C., Meyer D.: Comparison of Different Methods for Encoder Speed Signal Filtering Exemplified by an Inverted Pendulum, In Proc.: 2018 19th International Conference on Research and Education in Mechatronics (REM), pp. 1-6, IEEE, 2018.
[10] Puzdrowska P.: Signal filtering method of the fast-varying diesel exhaust gas temperature, Combustion Engines, 175(4), pp. 50-52, 2018.
[11] Masrom M. F., Ghani N. M., Jamin N. F., Razali N. A. A.: Stabilization Control of a Two-Wheeled Triple Link Inverted Pendulum System with Disturbance Rejection, In Proc.: 10th Na- tional Technical Seminar on Underwater System Technology 2018, pp. 151-159, Springer, 2019.
[12] Kovalchuk V. V.: Lyapunov's Stability Theory for a Triple Inverted Pendulum with a Follower Forces, Application of Mathematics in Computer Sciences, Maths in the Modern Technical University, In Proc.: VI International Scientific-Practical Conference Kyiv 2017, pp. 8, National Technical University of Ukraine, 2018.
[13] Ramirez-Neria M., Gao Z., Sira-Ramirez H., Garrido-Moctezuma R., Luviano-Juarez A.: Trajectory Tracking for an Inverted Pendulum on a Cart: An Active Disturbance Rejection Control Approach, In Proc.: 2018 Annual American Control Conference (ACC), pp. 4881-4886, IEEE, 2019.
[14] Zieli ´ nski, T. P.: Cyfrowe przetwarzanie sygnalow. Od teorii do zastosowan, Helion, 2007 (in Polish).
[15] Bhushana Rao K. Ch., Krishna B. T.: Comparative Analysis of Integer and Non-integer order Savitzky-Golay Digital Filters IEEE, 2017.
[16] Mohammadi-Moghaddam T., Razavi S. M., Sazgarnia A., Taghizadeh M.: Predicting the moisture content and textural characteristics of roasted pistachio kernels using Vis/NIR reflectance spectroscopy and PLSR analysis. Journal of Food Measurement and Characterization, 12(1), pp. 346-355, 2018.
[17] Liu J. G.: Smoothing Filter-based Intensity Modulation: A Spectral Preserve Image Fusion Technique for Improving Spatial Details, International Journal of Remote Sensing, 21:18, pp. 3461-3472, 2018.
[18] Einicke G. A.: Smoothing, Filtering and Prediction: Estimating the Past, Present and Future, 2012.
[19] Baranowski J., BauerW., Zagorowska M., Piatek P.: On Digital Realizations of Non-integer Order Filters, Circuits, Systems, and Signal Processing, 35, Issue: 6, pp. 20832107, 2016.
[20] Jahani S., Setarehdan S. K., Boas D. A., Yucel M.A.: Motion Artifact Detection and Correction in Functional Near-infrared Spectroscopy: A New Hybrid Method Based on Spline Interpolation Method and Savitzky–Golay Filtering, Neurophotonics, 5(1), pp. 015003, 2018.
[21] Pander T.: EEG Signal Improvement with Cascaded Filter Based on OWA Operator, Signal, Image and Video Processing, pp. 1-7, 2019.
[22] Panchuk V., Semenov V., Legin A., Kirsanov D.: Signal Smoothing with PLS Regression. Analytical chemistry, 90(9), pp. 5959-5964, 2018. 94