Óbuda University

PhD Thesis

Summary

New Soft Computing-based Methods in Sensor Fusion and Control: Applications on a Real Mechatronic System

by

Ákos Odry

Supervisor:

Prof. Dr. Róbert Fullér

Applied Informatics and Applied Mathematics Doctoral School

Budapest, 2020

Contents

1 Background of the Research

The overall performance of a closed-loop system depends on two important algorithms, these are the state estimator and controller. Since these algorithms are linked in a closed loop, therefore, it is a challenging issue to tune their parameters and thereby maximize the closed loop performance, especially if the system to be controlled is naturally unstable. Moreover, it is also difficult to determine whether a badly designed controller or state estimator results in unsatisfactory system behavior. Therefore, providing increased estimation convergence and effective control action and thereby producing enhanced closed loop performance are important issues to be addressed. As a result, this work deals with the preceding issues and proposes distinct approaches to enhance the system dynamics in closed loop.

For the elaboration and analysis of both control system design and state estimation problems, a test environment was required to be selected that enables the verification of developed techniques. Wheeled mobile pendulum robots (WMPs) have become popular mechatronic systems to be controlled in research works, commercial utilization and education Nagarajan (2012); Shomin (2016); Lilienkamp (2003); Zhaoqin (2012). These systems are characterized by advantageous electro-mechanical properties Li *et al.* (2012); Sciavicco and Siciliano (2012), moreover, the nonlinear underactuated configuration, presence of nonholonomic constraint and unstable open-loop behavior Chan *et al.* (2013) motivate the development of novel control techniques. As a result, an WMP system constituted the basis of the research, since it is an important benchmark system to verify the developed approaches.

This work focuses on the advantageous applicability of fuzzy logic-based inference systems for robotic applications. Zadeh's fuzzy logic introduced a new linguistic information based design perspective, where imprecision and uncertainty form the basis of the inference mechanism Zadeh (1965). The application of heuristic IF-THEN rules allows the expert to easily establish input-output relationships of the system to be designed based on deductions related to system dynamics Wang (1997). The provided flexibility, linguistic information-based design and heuristic knowledge oriented development capability enabled fuzzy control to be a popular technology in the development of robotic applications, such as unmanned air vehicles (UAVs) Kumon *et al.* (2006); Santos *et al.* (2010), mobile robots Das and Kar (2006); Hou *et al.* (2009); Huang *et al.* (2011); Anisimov *et al.* (2018) and walking robots Kecskés and Odry (2014). Moreover, it is widely investigated weather fuzzy logic-based control solutions can replace the linear approaches. In many applications fuzzy control showed superior performance McLean and Matsuda (1998); Tang *et al.* (2001); Kecskés and Odry (2014); Ahmed *et al.* (2016); Kecskés *et al.* (2017) over using linear techniques, however, the opposite outcome was often claimed as well Lee and Gonzalez (2008); Das and Kar (2006). These results confirm that the effective and beneficial applicability of fuzzy control still remains an important issue to be further addressed. Among the linear control techniques, the linear–quadratic–regulator (LQR) technique is a popularly used to control dynamical systems since it provides the optimal state feedback gains based on the mathematical algorithm Franklin *et al.* (1994). The successfully controlled dynamical systems include self balancing robots Jeong and Takahashi (2007); Shao and Liu (2010); Nagaya *et al.* (2013) and UAVs in uncertain environments Li *et al.* (2011); Araar and Aouf (2014); Bouabdallah *et al.* (2004), thereby confirming that competitive performance of LQR is regularly taken into account as a benchmark in comparative analyses Prasad *et al.* (2014); Nasir *et al.* (2010); Al-Younes *et al.* (2010); Márton *et al.* (2008); Xu *et al.* (2014); Guo *et al.* (2014); Dai *et al.* (2015); Sun and Li (2015); Xu *et al.* (2013).

Regarding the control system design of WMPs two approaches are prevalent. Linear controllers Lee and Jung (2012); Kim *et al.* (2006); Jeong and Takahashi (2008); Grasser *et al.* (2002) are designed considering the linearized mathematical model of the plant, and the control parameters are selected heuristically and tuned often by trial and error. However, the stability of the closed loop system is always an issue when the system leaves the neighborhood of the equilibrium, or uncertainty, unmodeled dynamics and disturbances present in the system. Usually in these cases advanced techniques are proposed. Among the advanced techniques, $\mathcal{H}_\infty$ control Raffo *et al.* (2015), sliding mode control (SMC) Yue *et al.* (2014); Xu *et al.* (2014); Guo *et al.* (2014); Dai *et al.* (2015); Ghaffari *et al.* (2016); Zhou and Wang (2016b) are quite common. Moreover, adaptive Sun and Li (2015); Ruck *et al.* (2016); Maruki *et al.* (2014); Cui *et al.* (2015), soft-computing techniques Huang *et al.* (2011); Xu *et al.* (2013); Yang *et al.* (2014), and also partial feedback linearization Pathak *et al.* (2005); Zhou and Wang (2016a); Yue *et al.* (2016) based methods are proposed in the literature. In many instances, the complex mathematical relations make the implementation difficult and too complicated due to both time variant and unknown parameters. On the other hand, there are many cases where the control action computation takes into account the physical parameters of the plant which are usually not validated. Therefore, a fuzzy control scheme that can be commonly used in practice, less complex and provides both easy implementation and effective control performance for WMPs still remains an important issue to be further addressed. Moreover, both linear and modern control approaches have been elaborated for this type of systems, however, the heuristic controller tuning was employed and in most cases and the achievable control performance has not been investigated, which also motivated my work.

Providing accurate attitude values as input to the applied control structure is essential for stabilizing the unstable WMP system. However, the relative orientation of a WMP body cannot be observed directly, instead, its attitude is estimated with estimation algorithms based on the measurement results of micro-electro-mechanical systems (MEMS). Usually trial and error methods are applied to set up the estimator algorithm Dai *et al.* (2015); Lee and Jung (2012); Huang *et al.* (2011), which results in a compromise performance. Additionally, there are two main types of disturbances that cause the WMP system attitude estimation to become unreliable, these are the external acceleration and external vibrations. These difficulties make the MEMS-based relative localization problem a crucial task to be solved. The MEMS inertial measurement unit (IMU) is utilized to track the real-time orientation of mobile platforms. An attitude and heading reference system (AHRS) is formed, which provides the complete orientation measurement relative to the global reference system Lee *et al.* (2012). The role of this algorithm is to combine the individual features of each sensor and provide both properly smoothed and robust attitude results.

Among the recent developments, Kalman-filters (KFs) and complementary filters (CFs), both augmented with the intelligent use of deterministic techniques, have become the most popular methods for robust attitude determination Wu and Shan (2019). Deterministic techniques solve Wahba's problem Wahba (1965) and provide attitude estimation based on gravity and magnetic field observations. The fundamental solutions are three-axis attitude determination (TRIAD) and the QUaternion ESTimator (QUEST). Improved approaches include fast optimal matrix algorithm (FOAM) Markley and Crassidis (2014), the factored quaternion algorithm (FQA) Yun *et al.* (2008), the Gauss–Newton algorithm Liu *et al.* (2014), Levenberg Marquardt algorithm Fourati *et al.* (2010), the gradient descent algorithm Madgwick *et al.* (2011), and super fast least-squares optimization-based algorithm Wu *et al.* (2018). The CF uses frequency domain information to synthesize signals that have complementary spectral components. This concept enables us to combine the slowly varying signals of the accelerometer and magnetometer with the fast signals of the gyroscope through low- and high-pass filters, respectively. The CF and its adaptive augmentation have been widely implemented in the robotics and control community Tian *et al.* (2012); Valenti *et al.* (2015), due to its simple structure and ease of implementation Euston *et al.* (2008); Tsagarakis *et al.* (2017), including UAVs Euston *et al.* (2008); Mahony *et al.* (2008) and human motion tracking Madgwick *et al.* (2011); Duraffourg *et al.* (2019); Fan *et al.* (2018) and their performances have regularly been considered in comparative analyses Cavallo *et al.* (2014); Valenti *et al.* (2015); Mourcou *et al.* (2015); Michel *et al.* (2018); Jouybari *et al.* (2019); Baldi *et al.* (2019). The KF and its extension for nonlinear cases, the extended KF (EKF), are the most prevalent Bayesian state estimation algorithms utilized for attitude determination. These recursive algorithms deal with statistical descriptions and predict the state of the Gaussian stochastic model of MARG with minimum variance. The main performance, which includes both the filter dynamics and convergence, is determined with the proper covariance matrices that describe the stochastic system. In most cases quaternion-based EKFs are developed for orientation tracking applications Sabatini (2006, 2011); Ligorio and Sabatini (2015); Makni *et al.* (2015); Nowicki *et al.* (2015); Zhang and Liao (2017), where adaptive strategies modify the noise covariance matrices if external disturbances occur Li and Wang (2013); Mazza *et al.* (2012); Roh and Kang (2018); Gośliński *et al.* (2015). Additionally, acceleration models are also incorporated in the stochastic model Lee *et al.* (2012); Yuan *et al.* (2019), and thus the implemented KF both estimates and compensates for the external acceleration in an attitude determination process. This discussion highlights that the procedure for selecting adequate filter parameters, thus providing enhanced filter convergence, remains an important issue. Moreover, the investigation of whether considering the magnitudes of inherent external acceleration, vibrations and magnetic perturbations as disturbance magnitudes in the estimation algorithm can improve filter robustness and accuracy remains also an important issue. Therefore, to develop new algorithms that provide both reliable and robust attitude estimates, especially for extreme dynamic situations motivated the work during my research.

2 Research Goals

Taking into account the continuously emerging potential of fuzzy logic and control, my research goals have been summarized into two parts.

On one hand, my goal was to both investigate and measure the achievable fuzzy control performance, and moreover, through the optimization and validation steps design novel fuzzy control structures that provide more robust control performance than conventional techniques.

This procedure enabled to investigate whether the flexibility and expert oriented inference nature of fuzzy logic can provide significant benefits over linear control techniques during the stabilization of a real mechatronic system. Additionally, the objective was to derive such fuzzy control strategies that is characterized by simple structure and easy implementation, where such expert oriented design approach is employed which uses those simple heuristic knowledge oriented tools that fuzzy logic meant to offer.

On the other hand, my goal was to address the attitude estimation problem of mobile robots and propose novel soft computing-based approaches that improve the estimation performance. Therefore, such techniques were analyzed that enable to overcome the compromise solution related to ad hoc state estimator tuning by finding such estimator parameters that provide maximized state estimation performance. Additionally, this analysis also includes the development of advanced state estimator structures, where the estimator parameters are modified (via adaptive techniques) based on external system dynamics measures and thereby a superior estimator performance is achieved.

The research objectives and the relevant tasks are summarized as follows.

- Deriving a reliable mathematical model of the plant and creating its simulation environment. Then, developing both fundamental linear controller-based stabilization approaches and modern fuzzy logic controller-based (FLC-based) solutions for the plant. Additionally, defining the control quality with performance indexes, and giving a detailed comparative assessment of the developed and realized control structures. At this stage the controller parameters are defined heuristically based on observations of the dynamics.

- Defining complex drive quality metrics, i.e., a complex cost (or fitness) function for the evaluation of the overall control quality; and applying numerical optimization to maximize the control performances, as well as, analyzing the advantages of fuzzy logic over linear techniques based on the results. Then, developing advanced FLCs based on heuristic knowledge that both provide efficient trajectory tracking and prevent high current peaks and jerks in motor drive system of robots.

- Developing a state estimator for the noisy states of the plant; and designing a test environment that enables simulations of various (accelerating and non-accelerating) system behaviors as well as measurement and qualification of the filter convergence. Then, analyzing both the state estimation performance based on quality metrics and the anomalies of fundamental estimation approaches. Applying numerical optimization to estimator parameters and achieving an optimized filter performance.

- Deriving a novel adaptive state estimator structure that fuses the magnitudes of the disturbances together and utilizes fuzzy-logic based heuristic IF-THEN rules that modify the parameters based on the dynamic behavior. Then, comparing the achieved estimation performances to popular algorithms and proving that the developed solutions are competitive and even outperform the common methods.

- Extending the aforementioned results and formulating the extended, quaternion-based state estimator structure that incorporates the magnitudes of vibration, external acceleration, and magnetic perturbation by a sophisticated heuristic knowledge-based fuzzy inference machine to provide robust attitude estimation in both static and dynamic environments. Moreover, designing a test platform which enables both the execution of various dynamic (vibrating and accelerating) behaviors in the three-dimensional space and the measurement of true attitude angles along with the raw MARG data. This test environment contributes to both the successful evaluation of state estimation quality and validation of the methods.

3 Methods of Investigation

Wheeled mobile pendulum

The mechatronic system had been realized before my research studies. During the research work I was continuously developing and extending its C language-based embedded software (two 16-bit ultra-low-power microcontrollers; hereinafter MCU1 and MCU2) to test and verify the control concepts. Low cost MEMS accelerometer and gyroscope sensors measure the dynamics of the inner body (IB) of the robot, and additionally, current sensors and two-channel incremental encoders are attached to both DC motors. The actuators (DC micromotors) are driven with PWM signals through motor drivers. MCU2 works as an IMU: it collects the measurements from the MEMS sensors through SPI peripheral, performs the state estimation and sends the results to MCU1 via its UART interface. MCU1 executes basically the control task. On one hand, it collects the measurements (from incremental encoders, current sensors, and from MCU2). On the other hand, it drives the motors based on the applied control algorithm. MCU1 also sends the measurements to the PC through a Bluetooth module.

Mathematical model

To be able to efficiently design the control algorithms of the system, its mathematical model has to be obtained first. As it was emphasized earlier, it is tedious, cumbersome task to set up, test and evaluate control strategies in real-time on the real physical system, especially if the system has unstable equilibrium points. Therefore, a realistic mathematical model and its simulation environment can speed up significantly the development process, moreover, it can prevent the realization of such control strategies that may drive the system out of equilibrium to unwanted states and/or damage the system and its environment. As a result, during the research process I developed a realistic mathematical model for the plant. The main software for this development process was the MathWorks MATLAB environment. The complete simulation model was established is Simulink, where the derived state space equations were implemented with S-Function Simulink blocks. The derived mathematical model includes both the nonlinear mechanical elements and the motor drive system of the robot. Similarly, for the state estimation problem, the derived linear and nonlinear state space models, the developed measurement methods, and heuristic inference machines were implemented and tested in MATLAB Simulink environment.

Control solutions

Similarly to the mathematical environment, the control structures were elaborated in MATLAB/Simulink environment. The linear control technique was based on the developed mathematical algorithm which results the optimal state-feedback gain that minimizes the quadratic cost function. The linearization of the mathematical model, controllability analysis, Control Algebraic Riccati Equation (CARE) and feedback matrix calculation was executed with built-in MATLAB functions. The FLCs were designed heuristically with the help of the Fuzzy Logic Toolbox of MATLAB, while the testing of the fuzzy control strategy was similarly performed in Simulink first. The implementation of the LQG approach was rather straightforward; the optimal gains and reference tracking matrices were directly applied to weight the state vector for the calculation of the control outputs once the measurements were updated. The implementation of the fuzzy control strategy was based on the fuzzy surfaces. Since fuzzy surfaces define the output of the controller as a function of the instantaneous inputs, FLCs can be approximated with look-up tables (LUT). This LUT based implementation method is suitable for small embedded processors and requires less calculation, because only the table indexes are needed to be calculated.

Optimization algorithm

The realized simulation environment was considered as a black box object characterized by its inputs, outputs and the parameters that determine the overall closed-loop performance. The particle swarm optimization algorithm (PSO) was applied for the tuning of the important parameters, since it is a robust and efficient (with a fast convergence), easy to implement heuristic method that has already proven its fast convergence property Kwok *et al.* (2006); Ye *et al.* (2017). In addition, PSO is a population-based search algorithm that uses the fitness function to guide the search in the search space; therefore, unlike gradient-based optimization methods, the PSO does not have difficulties with nonlinear, noisy, or discontinuous functions and is less susceptible to becoming trapped in local minima. In this work, I used the Particle Swarm toolbox for MATLAB Code (2013) to implement the algorithm.

Flexible fuzzy logic controllers

In case of the linear control approach, the parameters (optimal gains) were directly applied to weight the state vector for the calculation of the control action. Therefore, the optimization of these parameters was straightforward (these parameters were easily accessible). However, the fuzzy control approach was realized with FLC Simulink blocks initially in the simulation environment, which did not allow the effective tuning of fuzzy parameters. As a result, a flexible FLC MATLAB function was created and implemented in Simulink environment, which both enabled the effective tuning of fuzzy parameters and executed fuzzy logic inference based on the defined IF-THEN rules. This function allowed the tuning of the input-output membership functions (including singleton, triangular of Gaussian functions) and the range of the input and output variables. The weighting factor of each implemented rule could have been another adjustable parameter of the function, however, this was omitted during the implementation since I considered equally weighted rules in the realized rule bases.

Ground truth measurements

To evaluate the state estimation error and measure different filter performances the true state (i.e., the true attitude of the WMP body) was required to be known. First, a two degrees of freedom (DOF) test bench was designed, which provided a set of special circumstances to the WMP that allowed the real attitude angle to be measured and the accelerometer and gyroscope measurements to be collected. This test bench used two (shaft-clamping) jaws to pin down the wheel shafts and prevent their rotation. The test bench jaws were attached to a movable plate that slid back and forth on two parallel rails via linear bearings. The position of the plate was measured by the attached encoder. This electro-mechanical structure enabled external acceleration to occur simultaneously with the IB's oscillation, allowing a variety of dynamic (vibrating and accelerating) system behavior to be simulated and measured. The encoder measurements attached to the motor (the true attitude) and the sliding plate (the true horizontal acceleration), along with the instantaneous accelerometer and gyroscope data, were collected and sent to the PC for further evaluation. Then, a comprehensive framework was designed, in which a 6 DOF test bench dynamically altered the pose (position and orientation) of an IMU unit. This 6 DOF test bench was utilized to both simulate various (accelerating, non-accelerating, and vibrating) dynamic behaviors and measure the real attitude of the sensor frame, along with the raw IMU data. The framework was based on the Robot Operating System (ROS) and the Gazebo open source dynamics simulator. As a result, this framework enabled the evaluation of state estimation error, quantification of the filter performance, and tuning of filter parameters. The designed test bench consisted of three prismatic joints and three revolute joints. The prismatic joints made the sensor frame slide back and forth, up and down in the three dimensional (3D) space. The revolute joints set the instantaneous attitude (Euler angles) of the sensor frame. The IMU unit was attached to a plate at the end of this kinematic chain and, so, the 6 DOF system enabled both the spatial coordinates and orientation of the sensor frame to be set and measured. Moreover, this 6 DOF mechanism enabled the generation of external accelerations simultaneously with sensor frame oscillations. Therefore, a variety of dynamic (vibrating and accelerating) system conditions could be simulated, where both the raw sensor data and real joint states were recorded. Additionally, the magnetic perturbations were generated artificially, as the Gazebo simulation environment does not contain such a feature. A simple algorithm was developed which generated realistic magnetic perturbations during the measurement processes.

4 New Scientific Results

4.1 Thesis group I: Achievements in Control Performance Enhancement

This thesis group deals with the development and analysis of such fuzzy control approaches, which provide both robust dynamical behavior and energy efficient control actions in mechatronics (robotics) applications compared to conventional methods. The main result of the investigation is a special PI-type FLC structure, which limits the jerks and current transients in motor drive systems, thereby protecting efficiently the electro-mechanical parts of robots.

Thesis 1.1
A nonlinear 8-dimensional mathematical model of WMP systems has been derived that takes into account the motor dynamics, and its inputs are the terminal voltages of the applied motors. Based on the comparison of measurement and simulation results of open-loop robot dynamics, it was shown that the proposed model well describes the real behavior of the dynamical system, thus it provides the basis to effectively design control algorithms for these kind of underactuated naturally unstable mechatronic systems.

Publications pertaining to the thesis: Odry *et al.* (2015a,b).

Thesis 1.2
A cascade-connected, heuristic IF-THEN rules-based fuzzy control scheme has been developed for the unstable mechatronic system, which provides asymptotic stability in closed loop.

Publications pertaining to the thesis: Odry *et al.* (2016a, 2020a).

Thesis 1.3
A special PI-type FLC has been derived, which evaluates the instantaneous motor currents beside the error signals, thereby providing both smooth control action and improved control performance. A protective-type fuzzy control structure has been established with the derived FLC.

Publications pertaining to thesis: Odry *et al.* (2017b).

Thesis 1.4
An optimized fuzzy control structure has been obtained with the aid of the PSO algorithm. The outlined comparative analysis highlighted that the protective-type FLC structure provides significantly improved control performance than the linear approach in terms of the resulting oscillations and current peaks in the electro-mechanical structure of mechatronic systems.

Publications pertaining to thesis: Odry *et al.* (2016b, 2017a); Odry and Fullér (2018).

Remark: The byproduct of these theses is a novel educational project for both robotics and control system design laboratories. I both developed a laboratory setup (WMP kit) for education of (fuzzy-based) control problems and described a complete laboratory project from analysis of the solutions in the literature, over the description and elaboration of dedicated student tasks, to the assessment recommendations. This laboratory project is described in Odry *et al.* (2020a):

Odry, Á., Fullér, R., Rudas, I. J., and Odry, P. Fuzzy control of self-balancing robots: A control laboratory project. *Computer Applications in Engineering Education*, 2020, 1 − 24.

Moreover, all the information, including the computer aided design (CAD) models, MATLAB/Simulink files, MCU software, and LUT-based implementation of FLCs have been made publicly available in the supplementary online material Odry (2019b) to help other lab teams in designing similar experiments. This enables both the WMP lab kit and addressed control system design problems to be replicated in the laboratory of any institution. The complete project along with the software tools have been developed solely by the author of this PhD dissertation.

4.2 Thesis group II: Achievements in Estimation Quality Enhancement

This thesis group deals with the development and analysis of such soft computing-based methods, which provide enhanced state estimation performance in terms of robustness and accuracy for agile mechatronic systems executing both static and extreme dynamic motions.

Thesis 2.1
A fuzzy-adaptive KF has been established, which varies the filter parameters in real time based on the instantaneous system dynamics characterized by the magnitudes of external accelerations and vibrations. In this filter structure, the mapping between the instantaneous dynamics and KF parameters is realized by fuzzy-logic based heuristic IF-THEN rules. The proposed adaptive approach significantly improves the overall filter performance compared to the standard KF.

Publication pertaining to the thesis: Odry *et al.* (2018).

Thesis 2.2
A FAEKF structure has been derived, which incorporates both an EKF operating on quaternion-based orientation propagation and a sophisticated fuzzy inference machine. In this structure, the fuzzy inference system forms the relationship between the external disturbance (external acceleration, magnetic perturbation and vibration) magnitudes and EKF parameters and consistently modifies the noise variance values based on the instantaneous system dynamics. The developed adaptive structure effectively suppresses the effects of external disturbances, thereby enabling the FAEKF to provide reliable attitude estimation results, even in extreme dynamic and/or perturbed situations.

Publication pertaining to the thesis: Odry *et al.* (2020b).

Remark: The byproduct of these theses is a free-to-use ROS package I developed during my research work. This package enables both the generation of MARG-based measurements and the testing of different filter performances. I made this ROS package (which includes the developed test bench properties, URDF files, applied effort controllers, Gazebo configuration files and MATLAB scripts for the generation of artificial magnetic perturbation) publicly available in the supplementary online material Odry (2019a), with the aim of helping other laboratory teams with both performing and developing similar experiments. The complete project along with the software tools have been developed by the author of this PhD dissertation.

5 Practical Applicability of the Results

The research work addressed the enhancement of the closed loop performance of control systems and presented novel soft computing-based solutions to both improve the performance of control algorithms implemented for the stabilization of dynamical systems and provide accurate and robust state estimation results even if variable, dynamic-dependent operating system conditions are present. The tools and methods used in the analysis of WMP control are helpful results for the development of similar electro-mechanical constructions.

A realistic mathematical model for WMP system was derived, which forms the basis for the analyses of both robustness and stability issues of different control strategies. Moreover, the included nonlinear mechanical effects allows the developer to predict system behaviors outside of the equilibrium points. Since, the derived state space model has a compact form, the interested readers can use this model and simply initialize their simulation environment. The developed fuzzy control strategy was characterized by simple structure and clear rule-base, moreover, its straightforward, LUT-based implementation was demonstrated. The developed solutions represent a novel heuristic-type technique to provide satisfying reference tracking to robots and simultaneously protect the electro-mechanical parts against jerks and vibrations along with smaller energy consumption transients. The achieved control performances have shown that the flexibility of fuzzy logic provides an easy and effective way to improve the overall performance of the system.

Novel solutions for low-cost MEMS-IMU and MEMS-MARG based attitude estimation were established. Namely, new methods were developed for measuring instantaneous external disturbance magnitudes (external acceleration, vibration and magnetic perturbation). These methods provided relevant information of both the environment in which attitude estimation was performed and instantaneous system dynamics. The proposed methods can be universally applied to any motorized robotic system, where these measures are the primary sources of disturbance. Moreover, both the developed fuzzy inference machines and disturbance measurement methods can be used to tune other filters. This means that novel adaptive (nonlinear) complementary filters can be formed and their performances can be investigated for different mechatronic applications. Additionally, both the measurement methods and fuzzy inference mechanisms can be intelligently employed in adaptive control solutions for mechatronic systems performing motions in unknown and/or disturbed environments (e.g., wheeled/legged robots moving on uneven terrain or UAVs maneuvering in windy environments).

Bibliography

Ahmed, K., Yahaya, N., Asirvadam, V., Ramani, K., and Ibrahim, O. (2016). Comparison of fuzzy logic control and pi control for a three-level rectifier based on voltage oriented control. In *2016 IEEE International Conference on Power and Energy (PECon)*, pages 127–132. IEEE.

Al-Younes, Y. M., Al-Jarrah, M. A., and Jhemi, A. A. (2010). Linear vs. nonlinear control techniques for a quadrotor vehicle. In *7th International Symposium on Mechatronics and its Applications*, pages 1–10. IEEE.

Anisimov, D., Dang, T. S., *et al.* (2018). Development of a microcontroller-based adaptive fuzzy controller for a two-wheeled self-balancing robot. *Microsystem Technologies*, **24**(9), 3677–3687.

Araar, O. and Aouf, N. (2014). Full linear control of a quadrotor uav, lq vs hinf. In *2014 UKACC International Conference on Control (CONTROL)*, pages 133–138. IEEE.

Baldi, T. L., Farina, F., Garulli, A., Giannitrapani, A., and Prattichizzo, D. (2019). Upper body pose estimation using wearable inertial sensors and multiplicative kalman filter. *IEEE Sensors Journal*.

Bouabdallah, S., Noth, A., and Siegwart, R. (2004). Pid vs lq control techniques applied to an indoor micro quadrotor. In *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566)*, volume 3, pages 2451–2456. IEEE.

Cavallo, A., Cirillo, A., Cirillo, P., De Maria, G., Falco, P., Natale, C., and Pirozzi, S. (2014). Experimental comparison of sensor fusion algorithms for attitude estimation. *IFAC Proceedings Volumes*, **47**(3), 7585–7591.

Chan, R. P. M., Stol, K. A., and Halkyard, C. R. (2013). Review of modelling and control of two-wheeled robots. *Annual Reviews in Control*, **37**(1), 89–103.

Code, G. (2013). Particle swarm toolbox for matlab (psomatlab). Available from: code.google.com.

Cui, R., Guo, J., and Mao, Z. (2015). Adaptive backstepping control of wheeled inverted pendulums models. *Nonlinear Dynamics*, **79**(1), 501–511.

Dai, F., Gao, X., Jiang, S., Guo, W., and Liu, Y. (2015). A two-wheeled inverted pendulum robot with friction compensation. *Mechatronics*, **30**, 116–125.

Das, T. and Kar, I. N. (2006). Design and implementation of an adaptive fuzzy logic-based controller for wheeled mobile robots. *IEEE Transactions on Control Systems Technology*, **14**(3), 501–510.

Duraffourg, C., Bonnet, X., Dauriac, B., and Pillet, H. (2019). Real time estimation of the pose of a lower limb prosthesis from a single shank mounted imu. *Sensors*, **19**(13), 2865.

Euston, M., Coote, P., Mahony, R., Kim, J., and Hamel, T. (2008). A complementary filter for attitude estimation of a fixed-wing uav. In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, pages 340–345. IEEE.

Fan, B., Li, Q., and Liu, T. (2018). Improving the accuracy of wearable sensor orientation using a two-step complementary filter with state machine-based adaptive strategy. *Measurement Science and Technology*, **29**(11), 115104.

Fourati, H., Manamanni, N., Afilal, L., and Handrich, Y. (2010). A nonlinear filtering approach for the attitude and dynamic body acceleration estimation based on inertial and magnetic sensors: Bio-logging application. *IEEE sensors journal*, **11**(1), 233–244.

Franklin, G. F., Powell, J. D., Emami-Naeini, A., and Powell, J. D. (1994). *Feedback control of dynamic systems*, volume 3. Addison-Wesley Reading, MA.

Ghaffari, A., Shariati, A., and Shamekhi, A. H. (2016). A modified dynamical formulation for two-wheeled self-balancing robots. *Nonlinear Dynamics*, **83**(1-2), 217–230.

Gośliński, J., Nowicki, M., and Skrzypczyński, P. (2015). Performance comparison of ekf-based algorithms for orientation estimation on android platform. *IEEE Sensors Journal*, **15**(7), 3781–3792.

Grasser, F., D'arrigo, A., Colombi, S., and Rufer, A. C. (2002). Joe: a mobile, inverted pendulum. *IEEE Transactions on industrial electronics*, **49**(1), 107–114.

Guo, Z.-Q., Xu, J.-X., and Lee, T. H. (2014). Design and implementation of a new sliding mode controller on an underactuated wheeled inverted pendulum. *Journal of the Franklin Institute*, **351**(4), 2261–2282.

Hou, Z.-G., Zou, A.-M., Cheng, L., and Tan, M. (2009). Adaptive control of an electrically driven nonholonomic mobile robot via backstepping and fuzzy approach. *IEEE Transactions on Control Systems Technology*, **17**(4), 803–815.

Huang, C.-H., Wang, W.-J., and Chiu, C.-H. (2011). Design and implementation of fuzzy control on a two-wheel inverted pendulum. *IEEE Transactions on Industrial Electronics*, **58**(7), 2988–3001.

Jeong, S. and Takahashi, T. (2007). Wheeled inverted pendulum type assistant robot: inverted mobile, standing, and sitting motions. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1932–1937. IEEE.

Jeong, S. and Takahashi, T. (2008). Wheeled inverted pendulum type assistant robot: design concept and mobile control. *Intelligent Service Robotics*, **1**(4), 313–320.

Jouybari, A., Amiri, H., Ardalan, A. A., and Zahraee, N. K. (2019). Methods comparison for attitude determination of a lightweight buoy by raw data of imu. *Measurement*, **135**, 348–354.

Kecskés, I. and Odry, P. (2014). Optimization of pi and fuzzy-pi controllers on simulation model of szabad (ka)-ii walking robot. *International Journal of Advanced Robotic Systems*, **11**(11), 186.

Kecskés, I., Burkus, E., Király, Z., Odry, Á., and Odry, P. (2017). Competition of motor controllers using a simplified robot leg: Pid vs fuzzy logic. In *2017 Fourth International Conference on Mathematics and Computers in Sciences and in Industry (MCSI)*, pages 37–43. IEEE.

Kim, Y., Kim, S., and Kwak, Y. (2006). Improving driving ability for a two-wheeled inverted-pendulum-type autonomous vehicle. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, **220**(2), 165–175.

Kumon, M., Udo, Y., Michihira, H., Nagata, M., Mizumoto, I., and Iwai, Z. (2006). Autopilot system for kiteplane. *IEEE/ASME Transactions on Mechatronics*, **11**(5), 615–624.

Kwok, N., Ha, Q., Nguyen, T., Li, J., and Samali, B. (2006). A novel hysteretic model for magnetorheological fluid dampers and parameter identification using particle swarm optimization. *Sensors and Actuators A: Physical*, **132**(2), 441–451.

Lee, C. and Gonzalez, R. (2008). Fuzzy logic versus a pid controller for position control of a muscle-like actuated arm. *Journal of Mechanical Science and Technology*, **22**(8), 1475–1482.

Lee, H. and Jung, S. (2012). Balancing and navigation control of a mobile inverted pendulum robot using sensor fusion of low cost sensors. *Mechatronics*, **22**(1), 95–105.

Lee, J. K., Park, E. J., and Robinovitch, S. N. (2012). Estimation of attitude and external acceleration using inertial sensor measurement during various dynamic conditions. *IEEE transactions on instrumentation and measurement*, **61**(8), 2262–2273.

Li, W. and Wang, J. (2013). Effective adaptive kalman filter for mems-imu/magnetometers integrated attitude and heading reference systems. *Journal of Navigation*, **66**(01), 99–113.

Li, Y.-b., Liu, W.-z., and Song, Q. (2011). Improved lqg control for small unmanned helicopter based on active model in uncertain environment. In *2011 International Conference on Electronics, Communications and Control (ICECC)*, pages 289–292. IEEE.

Li, Z., Yang, C., and Fan, L. (2012). *Advanced control of wheeled inverted pendulum systems*. Springer Science & Business Media.

Ligorio, G. and Sabatini, A. M. (2015). A novel kalman filter for human motion tracking with an inertial-based dynamic inclinometer. *IEEE Transactions on Biomedical Engineering*, **62**(8), 2033–2043.

Lilienkamp, K. A. (2003). *Lab experiences for teaching undergraduate dynamics*. Ph.D. thesis, Massachusetts Institute of Technology.

Liu, F., Li, J., Wang, H., and Liu, C. (2014). An improved quaternion gauss–newton algorithm for attitude determination using magnetometer and accelerometer. *Chinese Journal of aeronautics*, **27**(4), 986–993.

Madgwick, S. O., Harrison, A. J., and Vaidyanathan, R. (2011). Estimation of imu and marg orientation using a gradient descent algorithm. In *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on*, pages 1–7. IEEE.

Mahony, R., Hamel, T., and Pflimlin, J.-M. (2008). Nonlinear complementary filters on the special orthogonal group. *IEEE Transactions on automatic control*, **53**(5), 1203–1218.

Makni, A., Fourati, H., and Kibangou, A. Y. (2015). Energy-aware adaptive attitude estimation under external acceleration for pedestrian navigation. *IEEE/ASME Transactions On Mechatronics*, **21**(3), 1366–1375.

Markley, F. L. and Crassidis, J. L. (2014). *Fundamentals of spacecraft attitude determination and control*, volume 33. Springer.

Márton, L., Hodel, A. S., Lantos, B., and Hung, J. Y. (2008). Underactuated robot control: comparing lqr, subspace stabilization, and combined error metric approaches. *IEEE Transactions on Industrial Electronics*, **55**(10), 3724–3730.

Maruki, Y., Kawano, K., Suemitsu, H., and Matsuo, T. (2014). Adaptive backstepping control of wheeled inverted pendulum with velocity estimator. *International Journal of Control, Automation and Systems*, **12**(5), 1040–1048.

Mazza, C., Donati, M., McCamley, J., Picerno, P., and Cappozzo, A. (2012). An optimized kalman filter for the estimate of trunk orientation from inertial sensors data during treadmill walking. *Gait & posture*, **35**(1), 138–142.

McLean, D. and Matsuda, H. (1998). Helicopter station-keeping: comparing lqr, fuzzy-logic and neural-net controllers. *Engineering Applications of Artificial Intelligence*, **11**(3), 411–418.

Michel, T., Genevès, P., Fourati, H., and Layaïda, N. (2018). Attitude estimation for indoor navigation and augmented reality with smartphones. *Pervasive and Mobile Computing*, **46**, 96–121.

Mourcou, Q., Fleury, A., Franco, C., Klopcic, F., and Vuillerme, N. (2015). Performance evaluation of smartphone inertial sensors measurement for range of motion. *Sensors*, **15**(9), 23168–23187.

Nagarajan, U. (2012). *Fast and graceful balancing mobile robots*. Ph.D. thesis, Carnegie Mellon University.

Nagaya, S., Morikawa, T., Takami, I., and Chen, G. (2013). Robust lq control for parallel wheeled inverted pendulum. In *2013 Australian Control Conference*, pages 189–194. IEEE.

Nasir, A., Ahmad, M., and Ismail, R. R. (2010). The control of a highly nonlinear two-wheels balancing robot: A comparative assessment between lqr and pid-pid control schemes. *World Academy of Science, Engineering and Technology*, **70**, 227–232.

Nowicki, M., Wietrzykowski, J., and Skrzypczyński, P. (2015). Simplicity or flexibility? complementary filter vs. ekf for orientation estimation on mobile devices. In *Cybernetics (CYBCONF), 2015 IEEE 2nd International Conference on*, pages 166–171. IEEE.

Odry, Á. (2019a). Fuzzy-adaptive Extended Kalman filter supplementary material. Available from: http://appl-dsp.com/faekf/.

Odry, Á. (2019b). Self-balancing robot supplementary material. Available from: http://appl-dsp.com/self-balancing-robot-kit/.

Pathak, K., Franch, J., and Agrawal, S. K. (2005). Velocity and position control of a wheeled inverted pendulum by partial feedback linearization. *IEEE Transactions on robotics*, **21**(3), 505–513.

Prasad, L. B., Tyagi, B., and Gupta, H. O. (2014). Optimal control of nonlinear inverted pendulum system using pid controller and lqr: performance analysis without and with disturbance input. *International Journal of Automation and Computing*, **11**(6), 661–670.

Raffo, G. V., Ortega, M. G., Madero, V., and Rubio, F. R. (2015). Two-wheeled self-balanced pendulum workspace improvement via underactuated robust nonlinear control. *Control Engineering Practice*, **44**, 231–242.

Roh, M.-S. and Kang, B.-S. (2018). Dynamic accuracy improvement of a mems ahrs for small uavs. *International Journal of Precision Engineering and Manufacturing*, **19**(10), 1457–1466.

Ruck, M., Herreros, I., Maffei, G., Sánchez-Fibla, M., and Verschure, P. (2016). Learning to balance while reaching: A cerebellar-based control architecture for a self-balancing robot. In *Conference on Biomimetic and Biohybrid Systems*, pages 214–226. Springer.

Sabatini, A. M. (2006). Quaternion-based extended kalman filter for determining orientation by inertial and magnetic sensing. *IEEE Transactions on Biomedical Engineering*, **53**(7), 1346–1356.

Sabatini, A. M. (2011). Kalman-filter-based orientation determination using inertial/magnetic sensors: Observability analysis and performance evaluation. *Sensors*, **11**(10), 9182–9206.

Santos, M., Lopez, V., and Morata, F. (2010). Intelligent fuzzy controller of a quadrotor. In *2010 IEEE international conference on intelligent systems and knowledge engineering*, pages 141–146. IEEE.

Sciavicco, L. and Siciliano, B. (2012). *Modelling and control of robot manipulators*. Springer Science & Business Media.

Shao, Z. and Liu, D. (2010). Balancing control of a unicycle riding. In *Proceedings of the 29th Chinese Control Conference*, pages 3250–3254. IEEE.

Shomin, M. (2016). *Navigation and physical interaction with balancing robots*. Ph.D. thesis, Carnegie Mellon University.

Sun, J. and Li, Z. (2015). Development and implementation of a wheeled inverted pendulum vehicle using adaptive neural control with extreme learning machines. *Cognitive Computation*, **7**(6), 740–752.

Tang, K.-S., Man, K. F., Chen, G., and Kwong, S. (2001). An optimal fuzzy pid controller. *IEEE transactions on industrial electronics*, **48**(4), 757–765.

Tian, Y., Wei, H., and Tan, J. (2012). An adaptive-gain complementary filter for real-time human motion tracking with marg sensors in free-living environments. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, **21**(2), 254–264.

Tsagarakis, N. G., Caldwell, D. G., Negrello, F., Choi, W., Baccelliere, L., Loc, V., Noorden, J., Muratore, L., Margan, A., Cardellino, A., *et al.* (2017). Walk-man: A high-performance humanoid platform for realistic environments. *Journal of Field Robotics*, **34**(7), 1225–1259.

Valenti, R. G., Dryanovski, I., and Xiao, J. (2015). Keeping a good attitude: A quaternion-based orientation filter for imus and margs. *Sensors*, **15**(8), 19302–19330.

Wahba, G. (1965). A least squares estimate of satellite attitude. *SIAM review*, **7**(3), 409–409.

Wang, L.-X. (1997). A course in fuzzy systems and control, prentice-hall ptr. *Englewood Cliffs, NJ*.

Wu, J. and Shan, S. (2019). Dot product equality constrained attitude determination from two vector observations: Theory and astronautical applications. *Aerospace*, **6**(9), 102.

Wu, J., Zhou, Z., Fourati, H., and Cheng, Y. (2018). A super fast attitude determination algorithm for consumer-level accelerometer and magnetometer. *IEEE Transactions on Consumer Electronics*, **64**(3), 375–381.

Xu, J.-X., Guo, Z.-Q., and Lee, T. H. (2013). Design and implementation of a takagi–sugeno-type fuzzy logic controller on a two-wheeled mobile robot. *IEEE Transactions on Industrial Electronics*, **60**(12), 5717–5728.

Xu, J.-X., Guo, Z.-Q., and Lee, T. H. (2014). Design and implementation of integral sliding-mode control on an underactuated two-wheeled mobile robot. *IEEE Transactions on Industrial Electronics*, **61**(7), 3671–3681.

Yang, C., Li, Z., Cui, R., and Xu, B. (2014). Neural network-based motion control of an underactuated wheeled inverted pendulum model. *IEEE Transactions on Neural Networks and Learning Systems*, **25**(11), 2004–2016.

Ye, Y., Yin, C.-B., Gong, Y., and Zhou, J.-j. (2017). Position control of nonlinear hydraulic system using an improved pso based pid controller. *Mechanical Systems and Signal Processing*, **83**, 241–259.

Yuan, Q., Asadi, E., Lu, Q., Yang, G., and Chen, I.-M. (2019). Uncertainty-based imu orientation tracking algorithm for dynamic motions. *IEEE/ASME Transactions on Mechatronics*, **24**(2), 872–882.

Yue, M., Wei, X., and Li, Z. (2014). Adaptive sliding-mode control for two-wheeled inverted pendulum vehicle based on zero-dynamics theory. *Nonlinear Dynamics*, **76**(1), 459–471.

Yue, M., An, C., and Sun, J. (2016). Zero dynamics stabilisation and adaptive trajectory tracking for wip vehicles through feedback linearisation and lqr technique. *International Journal of Control*, pages 1–10.

Yun, X., Bachmann, E. R., and McGhee, R. B. (2008). A simplified quaternion-based algorithm for orientation estimation from earth gravity and magnetic field measurements. *IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT*, **57**(3).

Zadeh, L. A. (1965). Fuzzy sets. *Information and control*, **8**(3), 338–353.

Zhang, T. and Liao, Y. (2017). Attitude measure system based on extended kalman filter for multi-rotors. *Computers and electronics in agriculture*, **134**, 19–26.

Zhaoqin, G. (2012). *Development and control of an underactuated two-wheeled mobile robot*. Ph.D. thesis, National University Of Singapore.

Zhou, Y. and Wang, Z. (2016a). Motion controller design of wheeled inverted pendulum with an input delay via optimal control theory. *Journal of Optimization Theory and Applications*, **168**(2), 625–645.

Zhou, Y. and Wang, Z. (2016b). Robust motion control of a two-wheeled inverted pendulum with an input delay based on optimal integral sliding mode manifold. *Nonlinear Dynamics*, pages 1–10.

Own Publications Pertaining to Theses

Odry, À. and Fullér, R. (2018). Comparison of optimized pid and fuzzy control strategies on a mobile pendulum robot. In *2018 IEEE 12th International Symposium on Applied Computational Intelligence and Informatics (SACI)*, pages 207–212. IEEE.

Odry, Á., Harmati, I., Király, Z., and Odry, P. (2015a). Design, realization and modeling of a two-wheeled mobile pendulum system. *14th International Conference on Instrumentation, Measurement, Circuits and Systems (IMCAS '15)*, pages 75–79.

Odry, Á., Burkus, E., and Odry, P. (2015b). Lqg control of a two-wheeled mobile pendulum system. *The Fourth International Conference on Intelligent Systems and Applications (INTELLI 2015)*, pages 105–112.

Odry, Á., Burkus, E., Kecskés, I., Fodor, J., and Odry, P. (2016a). Fuzzy control of a two-wheeled mobile pendulum system. In *Applied Computational Intelligence and Informatics (SACI), 2016 IEEE 11th International Symposium on*, pages 99–104. IEEE.

Odry, Á., Fodor, J., and Odry, P. (2016b). Stabilization of a two-wheeled mobile pendulum system using lqg and fuzzy control techniques. *International Journal On Advances in Intelligent Systems*, **9**(1,2), 223–232.

Odry, Á., Kecskes, I., Burkus, E., Kiraly, Z., and Odry, P. (2017a). Optimized fuzzy control of a two-wheeled mobile pendulum system. *International Journal of Control Systems and Robotics*, **2**, 73–79.

Odry, Á., Kecskés, I., Burkus, E., and Odry, P. (2017b). Protective fuzzy control of a two-wheeled mobile pendulum robot: Design and optimization. *WSEAS Transactions on Systems and Control*, **12**, 297–306.

Odry, Á., Fullér, R., Rudas, I. J., and Odry, P. (2018). Kalman filter for mobile-robot attitude estimation: Novel optimized and adaptive solutions. *Mechanical systems and signal processing*, **110**, 569–589.

Odry, Á., Fullér, R., Rudas, I. J., and Odry, P. (2020a). Fuzzy control of self-balancing robots: A control laboratory project. *Computer Applications in Engineering Education*, pages 1–24.

Odry, Á., Kecskes, I., Sarcevic, P., Vizvari, Z., Toth, A., and Odry, P. (2020b). A novel fuzzy-adaptive extended kalman filter for real-time attitude estimation of mobile robots. *Sensors*, **20**(3), 803.

Other Publications

Burkus, E., Bessenyei, S., Odry, Á., Kecskés, I., and Odry, P. (2016). Test bench built for the identification of the szabad (ka)-ii hexapod robot leg prototypes. In *2016 IEEE 14th International Symposium on Intelligent Systems and Informatics (SISY)*, pages 13–18. IEEE.

Kecskés, I., Odry, Á., Burkus, E., and Odry, P. (2016). Embedding optimized trajectory and motor controller into the szabad (ka)-ii hexapod robot. In *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 1417–1422. IEEE.

Kecskés, I., Burkus, E., Király, Z., Odry, Á., and Odry, P. (2017). Competition of motor controllers using a simplified robot leg: Pid vs fuzzy logic. In *2017 Fourth International Conference on Mathematics and Computers in Sciences and in Industry (MCSI)*, pages 37–43. IEEE.

Kecskés, I., Odry, Á., and Odry, P. (2019). Uncertainties in the movement and measurement of a hexapod robot. In *15th Conference on Dynamical systems theory and applications*. DSTA.

Odry, A., Toth, D., and Szakall, T. (2008). Two independent front-wheel driven robot model. In *2008 6th International Symposium on Intelligent Systems and Informatics*, pages 1–3. IEEE.

Odry, P., Mihaly, K., Sari, Z., Gobor, Z., Burkus, E., Kecskes, I., Kiraly, Z., Odry, A., Tadic, V., and Vizvari, Z. (2017). Robust solutions for complex systems. In *7th International Conference on Applied Internet and Information Technologies*, pages 1–9. ICAIIT.

Tadic, V., Odry, A., Kecskes, I., Burkus, E., Kiraly, Z., and Odry, P. (2019). Application of intel realsense cameras for depth image generation in robotics. *WSEAS Transactions on Computers*, **18**, 107–112.

Abstract

The performance of feedback control systems depends on two important algorithms. On one hand, measurements are collected of system dynamics based on sensor data and a state observer algorithm is executed to obtain an estimate of such system states that cannot be determined based on direct observations. This **state estimator algorithm** is the basis in many control engineering applications, since its output (system state estimate) is necessary to solve the control system design problem, i.e., the stabilization of the system around a desired state. As a result, the state estimator is required to provide both reliable and smooth results and thereby its performance directly influences the overall closed-loop dynamics. On the other hand, the **control algorithm** itself determines the performance of the feedback system. This algorithm should be able to satisfy all the essential control objectives based on both the observed and estimated system states. Moreover, the quality of regulation plays an important role, in which robustness against both parameter uncertainties and measurement noises is examined, as well as, smooth control action is addressed. The resultant control action can contribute to high-quality reference tracking, energy-efficient drive characteristics and/or protective (e.g., jerk-free) regulation, which are important aspects in the control of nowadays electro-mechanical systems (robots). In my research work, I analyzed the performance of the preceding algorithms and developed novel soft computing-based techniques to enhance the performance of both state estimation and control. The system to be discussed and controlled is a real wheeled mobile pendulum system, which is a simple two-wheeled mechatronic construction characterized by challenging control problems, such as underactuated, unstable and nonlinear dynamics.

The first group of theses addresses the control system design problem and investigates soft computing-based techniques to enhance the performance of control strategies. First, the realistic mathematical model of the plant is determined and verified based on measurement results of the real system behavior. This realistic model enables the consistent elaboration of stabilizing control strategies, testing of closed-loop dynamics, and the optimization of control parameters. As a result, a novel 8-dimensional mathematical model of wheeled mobile pendulum systems is obtained, which includes both the mechanical nonlinearities and motor dynamics. Then, linear and fuzzy logic-based control strategies are established for the stabilization of the unstable system and the initial performance of these controllers is determined based on both simulation and implementation results. In this stage of development process, the control strategies are designed and tuned heuristically based on the observations related to system dynamics. The development of performance maximizing approaches and the evaluation of the achievable control performances form the next step of the investigation. The quality of the realized control solutions is defined based on transient responses and different error integral formulas. Then, the numerical optimization of control parameters is outlined, where the enhancement of control solutions is realized via the minimization of the quality index (fitness or cost function). This optimization problem is elaborated in four main steps. First, an easily parameterized fuzzy logic control structure is realized in MATLAB/Simulink environment. Second, a complex fitness function is formulated for system dynamics qualification, which evaluates the reference tracking performance for planar motion, the oscillation of the inner body of the robot, and the energy efficiency of the implemented controllers. Third, the application of particle swarm optimization algorithm is elaborated with the aim to obtain the optimal possible controller parameters. Fourth, the achieved control performances are evaluated and a comparison of optimized linear and fuzzy control strategies is given. This investigation results in a novel protective-type fuzzy logic controller, which provides nonlinear control action based on the sampled current consumption. The structure of the this controller enables to both achieve fast reference tracking dynamics and suppress (limit) the current peaks and jerks in the electro-mechanical parts (motor drive system) of the robot.

The second group of theses deals with the enhancement of state (attitude) estimation performance and derives novel soft computing-based adaptive methods to provide reliable attitude estimates even in dynamic situations. First, the Kalman filter as state estimator algorithm is established for the system and the parameters of the algorithm are tuned heuristically based on real-time measurement results. The performance of this estimator algorithm is mostly influenced by the process and measurement noise covariance matrices, however the noise statistics is difficult to measure in real practical problems, especially in case of micro-electro-mechanical systems-based attitude estimation problem, where the assumed noises are dynamics-dependent. Therefore, the heuristically selected filter parameters yield only a compromise solution between filter accuracy and convergence. To overcome this issue, a filter testing environment is created and numerical optimization is performed to find the performance maximizing filter parameters, where both the raw sensor data and true states are obtained in a novel test environment. Then, new measurement methods are developed to obtain the instantaneous vibration and external acceleration magnitudes (thereby to characterize the system dynamics) and a novel adaptive filter structure is established. This filter structure consistently modifies the noise covariances based on the instantaneous system dynamics via a heuristically defined fuzzy inference machine. The measurement results highlight that the adaptive filter structure provides superior convergence even in extreme dynamic situations based on the comparative assessment of existing popular attitude estimator algorithms. Finally, the generalization of the adaptive filter is derived for quaternion representation of orientation. This filter structure incorporates an extended Kalman filter, three measurement methods for real-time determination of vibration, external acceleration and magnetic perturbation magnitudes, and a sophisticated fuzzy inference machine to vary the filter parameters based on the instantaneous dynamics. A novel test environment is developed for filter performance evaluation, where a six degrees of freedom test bench both enables the execution of various system condition and simultaneously measure the real states and raw sensor data. The experimental results show that the derived filter significantly improves the robustness of state estimation, both in static and extremely vibrating and accelerating environments. The developed dynamic-dependent feature makes the filter structure a suitable candidate for attitude estimation in mechatronic systems operating in variable conditions.

Keywords: *Kalman-filter, Fuzzy Logic Control, Optimization, Adaptive-filter, Attitude Estimation, Inertial Measurement Unit, Self-balancing Robot*

Új lágy számítási módszerek alkalmazása a szenzorfúzióban és irányításban: valós alkalmazások egy mechatronikai rendszeren

Odry Ákos

Kivonat

Mechatronikai rendszerek dinamikus viselkedésének minőségét alapvetően két fontos algoritmus befolyásolja zárt körben. Egyrészt, az állapotbecslő algoritmus szolgáltat hasznos eredményeket a nem mérhető vagy zajos állapotokról. A becslések a rendszer dinamika és a megfigyelhető rendszer kimenetek szenzorfelületen keresztüli méréseit felhasználva kerülnek előállítása. Az algoritmus illesztése a problémához és paramétereinek hangolása egy kritikus mérnöki feladat, hiszen az irányítás (szabályozó tervezés), mely a szakaszt a kívánt állapotok környezetében stabilizálja, az előállított becsléseket felhasználva kerül kidolgozásra. Az állapotbecslő az aszimptotikus becslés mellett különböző tervezési követelményeket kell, hogy kielégítsen valós mérnöki problémákban, ilyenek a minimális hiba dinamika és gyors konvergencia. Ennek következményeként megállapítható, hogy algoritmus performanciája szignifikánsan befolyásolja az elérhető dinamikát zárt körben. Másrészt, az alkalmazott irányítási algoritmus (szabályozó) performanciája határozza meg a zárt kör karakterisztikáját. Ez az algoritmus az irányítási követelmények teljesülését biztosítja a megfigyelt és becsült állapotok visszacsatolásán keresztül. Ezen túl pedig, az irányítás minősége tölt be fontos szerepet a szabályozó tervezése során, hiszen a szabályozók struktúrája robusztusan (a paraméterbizonytalanság, rendszer zaj és külső zavarás mellett) kell, hogy biztosítson stabilizáló bemenő jeleket az irányítandó rendszer számára. A realizált irányítás minősége több szempontból vizsgálható, a minőségi alapjel követésen keresztül, az energia hatékony irányítási karakterisztikán át, az elektromechanikai rendszerek felépítését kímélő megoldás hatékonyságáig. A disszertációban a fenti két algoritmus karakterisztikáit vizsgálom és új lágy számítási módszereken alapuló megoldásokat fejlesztek és alkalmazok, melyek a zárt kör eredő dinamikáját tökéletesítik az állapotbecslési és irányítási performanciák finomításán keresztül. A kutatás során olyan eszközre volt szükség, amely lehetővé teszi a kifejlesztett technikák beágyazását, tesztelését és verifikálását. Az erre alkalmas mechatronikai rendszer a kutatásokban és az iparban is elterjedt kétkerekű önegyensúlyozó robot, hiszen az egyszerű felépítésének ellenére kihívások tömkelegét tárja elénk, a komplex dinamikus viselkedéstől, a nemlineáris hatásokon át, az instabil munkapontig.

Az első téziscsoport olyan fuzzy szabályozók kifejlesztésével foglalkozik, amelyek robusztusabb dinamikus viselkedést és hatékonyabb energiafogyasztást biztosítanak robotikai alkalmazásokban, mint a közkedvelt megoldások. A feladat a zárt kör megtervezését, a mechatronikai rendszer stabilizálását és az elérhető irányítási performancia maximalizálását foglalja magába. A kidolgozás a választott mechatronikai rendszer (robot) valósághű modelljének meghatározásával indul, mely lehetővé teszi az irányítások következetes tervezését, tesztelését, realizálását és későbbi optimalizációját. A kutatás eredményeként megadom az önegyensúlyozó robotok 8-dimenziós nemlineáris dinamikus modelljét, mely a nemlineáris mechanikai hatások mellett a meghajtó motorok dinamikáját is magában foglalja. A következő kutatási lépésként a lineáris és fuzzy logikán alapuló irányítások - fuzzy logikai szabályozók – tervezésével foglalkozom. A sikeres tervezést pedig a realizáció követi, mely az implementációt és tesztelést foglalja magába a valós mechatronikai rendszeren. Ebben a fázisban az irányítások heurisztikus módon vannak megtervezve a szakasz dinamikus viselkedésének megfigyelésén keresztül. A realizált irányításokkal elérhető irányítási performanciák kiértékelése képezi a kutatás következő fázisát. Az irányítások minőségét a tranziens viselkedések és különböző hiba integrálok kiértékelésével jellemzem. A numerikus optimalizáció esetében az irányítási minőség javítása költségfüggvény

(fitness függvény) minimalizációs feladat. Az alkalmazott optimalizációs stratégiát négy fontos részre bontom. Első lépésként létrehozok egy paraméterezhető fuzzy következtető gépet és a hozzá tartozó MATLAB/Simulink teszt környezetet. Ezután, a dinamikus viselkedést egy komplex költségfüggvénnyel minősítem, mely figyelembe veszi a transzlációs mozgás dinamikáját, a közbenső test oszcillációját, valamint az implementált irányítás energia hatékonyságát. Harmadik lépésben alkalmazom a részecskeraj algoritmust az optimális szabályozó paraméterek megtalálása céljából. Végül pedig kiértékelem és összehasonlítom az optimalizált (vagy maximalizált) lineáris és fuzzy irányítási performanciákat. A fenti vizsgálatok eredményeként egy speciális fuzzy logikai szabályozó kerül definiálásra, mely áram tranziens limitáló mechanizmussal van felvértezve. A speciális struktúrának köszönhetően az áram tranziensek és oszcillációk sokkal kisebb mértékben jelentkeznek a robot elektromechanikai rendszerében a realizált fuzzy irányítás esetében, mint a lineáris irányításoknál.

A második téziscsoport az állapotbecslés minőségének tökéletesítését tárgyalja és olyan újszerű, lágy számítási módszereken alapuló technikákat vizsgál, melyek a megbízható becslési eredmények biztosítása mellett finomított performanciát mutatnak extrém dinamikus szcenáriókban is. A választott rendszer esetében a közbenső test orientációja képezi a nem mérhető és zajos rendszer állapotot. Az orientáció becslésére elterjedt megoldás a Kalman-szűrő (állapotbecslő) alkalmazása. Az algoritmus performanciáját az állapotegyenletben definiált zajok kovariancia mátrixai határozzák meg. Azonban, a legtöbb valós alkalmazásban a kovariancia mátrixok értékei nem mérhetők, ezért azok beállítása nem egyértelmű feladat. Továbbá, sok esetben a mérnöki intuíció és/vagy trial-and-error alapú hangolások csak kompromisszumos megoldásokat eredményeznek, mely kritikus kimenetelt eredményezhet instabil rendszerek szabályozása esetén. A téziscsoportban két új megoldást mutatok be az állapotbecslő performanciájának tökéletesítésére. Először kialakítok egy speciális teszt környezetet, melyben a szakasz valós (nem mérhető) állapota mérhetővé válik a realizált állapotértékek mellett. A mérési eredményeket felhasználva a szűrő paraméterek optimalizációját dolgozom ki a kialakított szimulációs környezetben. Ezt követően egy adaptív-fuzzy állapotbecslő struktúrát definiálok, mely a pillanatnyi vibrációk és külső gyorsulások (azaz a rendszer dinamikus viselkedésének) figyelembevételével online módosítja a szűrőparamétereket, ezáltal tovább javítva a becslési konvergencia minőségén. A kifejlesztett adaptív szűrő performanciáját két populáris állapotbecslő algoritmussal hasonlítom össze. A kutatás következő lépésében, ezt az adaptív szűrő struktúrát kiterjesztem és általánosítom kvaternió alapú orientáció becslésre. Az általános szűrő struktúrában kiterjesztett Kalman-szűrőt alkalmazok; a pillanatnyi külső zavarásokat mérőszámokkal jellemzem három új mérési módszer (vibrációk, külső gyorsulások és mágneses zavarások) segítségével, valamint egy kifinomult fuzzy következtetési gép segítségével HA-AKKOR szabálybázist implementálok a szűrőparaméterek következetes, online módosítására. Az adaptív szűrő orientáció becslésének konvergenciáját a háromdimenziós térben egy új teszt környezetben értékelem ki, ahol egy hat szabadságfokú mechatronikai rendszer lehetővé teszi különböző dinamikus viselkedések szimulálását és mind a valós rendszerállapotok mind pedig az érzékelő adatok szimultán mérését. A különböző szcenáriókban (kevert statikus és extrém dinamikus viselkedések mellett) elvégezett mérési eredmények a kifejlesztett adaptív szűrő robusztus karakterisztikáját bizonyítják. A kiváló eredmények a szűrő dinamika-alapú tulajdonságainak köszönhető, hiszen a szűrő paraméterek konzisztens változtatása az érzékelőkel realizált szögpozíciók előnyös fuzionálását teszi lehetővé.