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Mechatronic approach in application to solution of research and design problems

A. Martowicz[a,*], M. Ciszewski[a], T. Buratowski[a], A. Gallina[a], M. Rosiek[b], K. Seweryn[c], W. Teper[d], A.J. Zwierzyński[d], T. Uhl[a]

[a] AGH University of Science and Technology, Department of Robotics and Mechatronics, Al. A. Mickiewicza 30, 30–059 Krakow, Poland
[b] MONIT SHM Sp. z o.o., ul. Lublańska 34, 31–476 Krakow, Poland
[c] Polish Academy of Sciences, Space Research Centre, ul. Bartycka 18A, 00–716 Warszawa, Poland
[d] AGH University of Science and Technology, Department of Drilling and Geoengineering, Al. A. Mickiewicza 30, 30–059 Krakow, Poland

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ABSTRACT

In this paper, universality of the mechatronic approach is confirmed with the examples of highly specialized and innovative systems, recently developed for a very specific applications. As shown, similar design steps, tools and testing procedures may lead to effective solutions even for distant and challenging research areas. First, an Ultralight Mobile Drilling System, dedicated to extraction of soil and rock probes from subsurface regions, is presented. For this case, minimization of mass and high mobility of the system, whilst maintaining performance of bigger drilling rigs, required during operation in space environment, is taken into account. The presented design consists of a four-wheeled rover with adjustable rocker mechanism, a multifunctional core drilling module and a support module with manipulation capabilities and dedicated sample storage. Second, entire design process for fully scalable and reconfigurable data-based system for monitoring of technical condition for mechanical constructions is introduced. The system is based on the measurements of electromechanical impedance, which are carried out with piezoelectric transducers. Both presented systems successfully passed the laboratory and industrial tests and, therefore, confirmed correctness of the choices made with the applied design procedures. All aspects of the mechatronic approach were investigated to construct fully functional prototypes designed for different tasks and to deal with different environmental conditions.

1. Introduction

Practical aspects of introduction of the mechatronic philosophy into designing process are undeniable. Simultaneous design of mechanical and electronic parts integrated with computer science and elaboration of control algorithms leads to multifunctional, scalable and reconfigurable products with short time-to-market period [1]. Moreover, available tools for virtual and rapid prototyping allow for reliable solutions at early stages of designing and manufacturing processes as well [2,3]. Robots and mobile platforms remain of special researchers' attention concerning mechatronic approach [4–6].

The overall aim of the paper is to confirm universality of the mechatronic approach with the examples of novel systems, recently developed for a very specific applications. As shown, similar design steps, tools and testing procedures may lead to effective solutions even for distant and challenging research areas. The systems, which are presented in the work, successfully passed the laboratory and industrial tests and, therefore, confirmed correctness of the choices made with the applied design procedures. All aspects of the mechatronic approach were investigated to construct fully functional prototypes designed for different tasks and to deal with different operational conditions.

The work presents two applications of the mechatronic approach to entire designing and testing process in the fields of autonomous robots and Structural Health Monitoring (SHM). Both systems were developed with contribution of the Department of Robotics and Mechatronics at AGH University of Science and Technology, Krakow, Poland. In the following two introductory subsections, an overview regarding the above mentioned research areas is given to provide necessary state-of-the-art.

1.1. Drilling platforms and robots

Drilling process usually requires heavy machinery and dedicated equipment, transported to the drilling site that is mostly operated manually. In remote places and extraterrestrial environment

* Corresponding author. Te.: +48126173640.
E-mail address: adam.martowicz@agh.edu.pl (A. Martowicz).

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a totally different approach is needed. The mechatronic system presented in this paper is able to reach a designated place and autonomously perform drilling with sample extraction and storage. Due to transport reasons, the mass must be minimized and compactness of the system is an important factor. In the Earth environment, the Ultralight Mobile Drilling System (UMDS) could be transported by an Unmanned Aerial Vehicle to not easily accessible places. The subsystems can be also adapted to operation in extraterrestrial conditions. The main objective of the core drilling operation is to collect and secure soil and rock samples gathered from subsurface regions and provide them for further analysis that can give more comprehensive information than samples collected from the surface.

Analogous systems have not been designed for the Earth applications, however, there exist several solutions intended for space missions. Honeybee Robotics company designed a drilling rig for the experiment MARTE (Mars Astrobiology Research and Technology Experiment) described in [7]. The depth of 6 m was reached after 23 days of drilling in a laboratory environment. A drilling device, the Apollo Lunar Surface Drill, was employed manually during a space mission on the Moon and provided samples from the depth of 3 m [8]. The Luna 16 robotic probe managed to collect specimen from the 350 mm depth and it was the deepest autonomously drilled hole [9]. The European Space Agency develops a drilling system for the ExoMars mission that is equipped with a large 6-wheeled rover and core drilling module capable of drilling to the depth of 2 m according to [10]. The majority of presented drilling systems utilize large scale rover featuring 6-wheeled designs that can host various equipment for investigation of an unknown environment.

In the preliminary state of the concept for the system described in this paper, the tracked robot platform was taken into consideration, which was presented in work [11]. The general idea of the tracked mobile platform design was also described in work [4]. A mobile robotic wheeled platform was chosen on the basis of ADAMS simulations. The design and testing process of the platform that can produce 2 m deep holes and extract samples is presented.

1.2. Electromechanical impedance based SHM systems

An interdisciplinary approach is required in the SHM to face all research areas involved in the process of condition assessment [12,13]. Hence, dedicated systems integrating electrical and mechanical engineering, as well as material and computer sciences are desired to allow for effective and reliable inference on the current condition of a monitored structure [14,15]. Electromechanical impedance based SHM systems do not comprise an exception [16–18]. These systems require knowledge on the properties of permanently installed piezoelectric transducers (PZT) and monitored structure, preferably based on constitutive models and mechanical characteristics. Moreover, algorithms to control operation of all systems' components, i.e., sensors and electronic circuits used for signal conditioning, are developed. Finally, computer science is employed to direct messages with the measured quantities circulating in a database-based system. Finally, after configuration, the systems are ready for local damage detection.

In case of electromechanical impedance measurements the integrity of a structure is checked by locally generated vibrations at frequencies from the range 10 kHz up to 500 kHz. Similarly, a damage can be identified in the area of the radius up to tens of centimeters thanks to the electromechanical coupling in the installed PZTs [16,19]. The described approach is a baseline-based method. The assessment on the technical condition is carried out with damage indexes, which reflect changes in periodically measured frequency characteristics. The SHM system allows to find and track an incipient and growing damage. Discussion on influence of operational conditions, including temperature and contact effects on the reliability of the electromechanical impedance based SHM systems can be found in recent works [20–22].

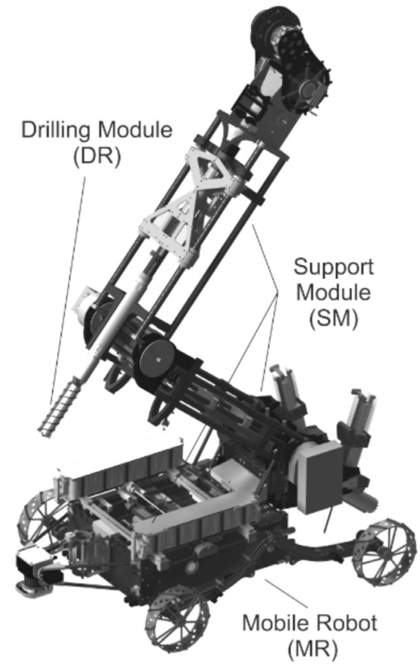

Fig. 1. Mobile drilling system - overview of the subsystems.

Taking into consideration high quality of the currently available measurement systems equipped with PZTs, it is now feasible to continuously and reliably monitor the condition of a machine or structure and, therefore, prevent from catastrophic failures [23]. Necessary changes in machinery components can be made early enough [24]. The current work presents several successful applications of the developed SHM system for both laboratory and industrial cases.

1.3. Agenda of the paper

The following provides with a comprehensive overview on the design and testing process for the two previously mentioned research cases. Substantially different research cases are intentionally addressed by the authors in Sections 2 and 3, respectively, to show vast application range for the mechatronic approach used for novel constructions and systems. The subsequent designing steps, which are consistently shown in subsections, cover a system overview as well as its general requirements, mathematical modelling and preliminary tests of the prototypes. The mobile platform of the drilling robot is characterized, with detailed description of electronic components and mechanics in the aspect of mobility and navigation. For the second research case, the components of the SHM system are characterized and the functionality of the whole system is discussed. The results of the analyses for industrial operational conditions are shown as well. Final Section 4 summarizes the paper and draws concluding remarks.

2. Mechatronic design of an ultralight mobile drilling system

2.1. System overview

The UMDS is based on three main subsystems that cooperate in the consecutive steps of the mission as depicted in Fig. 1. The Mobile Robot (MR) subsystem is responsible for motion and negotiation of obstacles in harsh environment. Drilling Module (DR) is