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Original scientific paper

DESIGN OF CARTESIAN ROBOT TEST RIG FOR ANGULAR POSITION SENSORS

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A b s t r a c t: A design solution for a test rig is proposed, intended for experimentation with angular position sensors. The test rig utilizes a Cartesian robot (gantry robot) with an additional axis for the purpose of implementing rotational motion. In addition, this test rig introduces a supervisory control system (SCS) for the purpose of: interacting with the user, acquiring and recording measurement results from an oscilloscope, coordination between the motion of robot and oscilloscope measurement actions. The test rig will provide a remote access with real-time video stream that will enable control and monitoring activity from Wide Area Network (WAN). The design incorporates a goal of a low cost build while achieving a reasonable motion accuracy for the testing purposes of a common angular position sensor. Furthermore, the build is designed to be modular and flexible enough to be repurposed for future educational uses in the field of robotics. The design envisages a solution that should require the least amount of custom developed technologies, utilizing already available and widely used mechanical and electrical hardware components, as well as software tools and libraries.

Key words: test rig; Cartesian robot; XYZR robot; angle sensor; inductive sensor; eddy-currents

ПРОЕКТИРАЊЕ НА ЕКСПЕРИМЕНТАЛНА ПЛАТФОРМА СО ДЕКАРТОВ РОБОТ ЗА ТЕСТИРАЊЕ НА СЕНЗОРИ ЗА МЕРЕЊЕ АГОЛНА ПОЗИЦИЈА

А п с т р а к т: Претставено е проектирано решение за експериментална платформа наменета за експериментирање со сензори за мерење аголна позиција. Експерименталната платформа користи Декартов робот со дополнителна оска за имплементирање на кружно движење. Претставен е систем за надзорно управување (СНУ) со намена: комуникација со корисникот, прибирање и зачувување мерни резултати од осцилоскоп, координација помеѓу движењето на роботот и мерните дејства на осцилоскопот. Експерименталната маса нуди далечински пристап со видео-приказ во реално време, така што се овозможуваат управувачки и надзорни активности од регионална мрежа (WAN). Проектот нуди економично решение со задоволителна прецизност во движењето на роботот, применливо за најчесто користените сензори за аголна позиција. Дополнително, решението е проектирано да биде модуларно и доволно флексибилно за идна пренамена за образовни цели во полето на роботиката. Проектот е предвиден да користи минимален број посебно изработени технологии, така што ќе искористи веќе пристапни и широко користени машински и електрични хардверски компоненти, софтверски алатки и библиотеки.

Клучни зборови: експериментална платформа; Декартов робот; робот XYZR; аголен сензор; индуктивен сензор; вртложни струи

1. INTRODUCTION

The automotive industry faces novel and innovative sensor solutions on a consistent basis, as a result of the gradual and undeniable transition towards electric vehicles (EVs). The demand for innovation and development in the EV industry has led to a development and requirement for new type of sensors and actuators. Robust and low cost angle sensors, with acceptable accuracy, are unquestionable necessity in the automotive industry with wide applications for throttle positioning, steering wheel sensing, pedal position sensing, electric motor control [1–3]. Many of these sensors utilize different sensing techniques such as [4]: capacitive, inductive, hall-effect or optical angle sensors.

Among these sensors, an inductive eddy-current type of sensor with planar coils has taken space in the automotive market [5–10]. This type of sensor is not affected by contamination like dust, moisture, grease, oil, or other materials as long as they are nonmagnetic. Furthermore these sensors provide considerable robustness to variable temperature conditions and mechanical vibrations which are common in the automotive environment. Finally, the ease of manufacturing and low cost makes these sensors a very viable solution for the automotive industry. Multiple designs of sensors have been suggested in the literature [11–17] that were based on this working principle and this work is intended for the development and research of one such sensor.

Namely, a design solution for a test rig shall be suggested with the intention of experimentation with an angular position sensor. The proposed test rig should allow for executing automatic test measurements on the sensor for variable rotational and translational displacements. Consequently the acquired measurement data will enable analysis and optimization of the sensor during research and development. Novel research work on angular position sensors is omnipresent in the field, however rarely do the authors mention the details related to the utilized test rig intended for performing tests on the sensor. A design of a Cartesian robot is presented in several works [24–27], however its utilization does not encompass a test rig for angular position sensors. To the best of our knowledge, a detailed design solution for such a testrig has not been covered by present literature, therefore the aim of this work is to put forward the intricacies of said design.

For this purpose, a Cartesian robot is proposed with an additional axis for executing rotational motion in the sensor. The Cartesian configuration of the robot was determined to be the most appropriate solution because of its ease of use and widely available software libraries for motion control. Considering the simplicity of a decentralized multi-joint control [18], which is applicable in this type of configuration, control of the whole robot is based on individual single-joint control for each axis. Furthermore, this type of configuration is utilized pervasively in the industry through various applications such as: pick and place, material handling and packaging, laboratory experiments, assembly, and other applications in manufacturing [19]. In addition, the test rig shall provide a remote access for control and monitoring activities from WAN being mediated from a supervisory control system (SCS) which will also coordinate between motion of the robot and measurement actions of the test rig.

This paper is organized as follows. In Section 2 the utilization purpose of the test rig and design goals are presented. In Section 3 the proposed mechanical design is described. The necessary details in regards to electrical and software design are provided in Section 4. In Section 5, the main conclusions are drawn along with plans for future work.

2. TEST RIG PURPOSE

a) *Requirements*

Most contactless angle sensors are comprised of two parts: stator and rotor. The stator is the active part of the sensor which most commonly contains the electrical circuits for providing angular measurement output while the rotor is the moving part that passively causes changes in the measured signals. The intended purpose of the test rig is to implement precise rotational motion in the rotor so as to perform measurements of the signals obtained for different angular displacements. However apart from rotational displacement, non-contact angle sensors can demonstrate different output results for XYZ displacements in the Cartesian space as well. Considering that the rotor and stator almost never experience an ideal mechanical arrangement in practical implementation, it is important for the test rig to provide testing ability for such cases.

Namely, a displacement in the Cartesian space may provide information in regards to: signal strength, measurement sensitivity, influence and susceptibility to errors due to mechanical sensor arrangement, influence of different types of materials in nearby proximity, optimal mechanical placement of stator and rotor, etc. Figure 1 illustrates different possible examples of test cases with an angular position sensor.

Robot motion in the Cartesian space should be as precise as possible in order to achieve reproducible measurement results. Furthermore, it is required from the test rig to coordinate motion of the robot in accordance with the obtained measurements. Consequently, each incremental motion of the robot should be realized only after the measurement results have been obtained for the appropriate angle.

This allows for proper designation of each measurement according to the position of the rotor in relation to the stator.

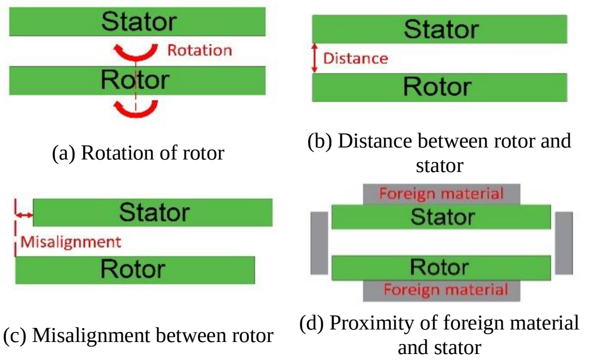

Fig. 1. Various test cases for an angular position sensor

In addition, a remote access to the test rig will provide additional ease of use. Instead of requiring physical presence for each experimental activity, it will be possible to initiate tests with remote access from Wide Area Network (WAN) or Local Area Network (LAN). This approach will drastically simplify utilization of the test rig in case it is placed in a different room or different geographical location.

b) *Architecture*

In order to accomplish the mentioned requirements in Section 2-a), a complete architecture of the system is proposed in Figure 2. As illustrated, the Cartesian robot is comprised of 4 degrees of freedom with three prismatic joints for motion through Cartesian space and one revolute joint for executing rotational motion in the rotor.

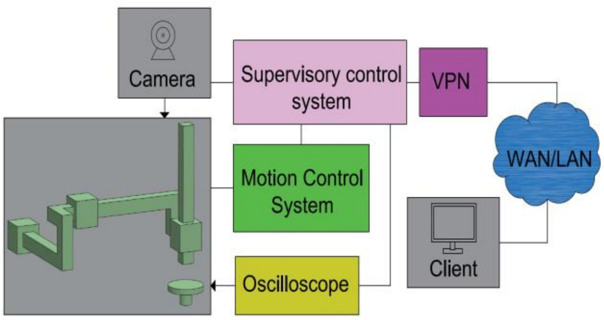

Fig. 2. Test rig architecture

The motion of the robot will be controlled through a dedicated motion control system (MCS) which can be deployed on most widely spread embedded development boards. A supervisory control system (SCS) will communicate with an oscilloscope to initiate measurements. Concurrently the same system will coordinate motion of the robot in between measurements. The SCS will also provide a Graphical User Interface (GUI) for setup and monitoring activities as well as data acquisition in relation to measurements. The same GUI will be accessible through LAN and WAN, allowing for a remote access. For security reasons, access from WAN will only be available through a VPN service. In addition, a camera will be utilized for real time video stream in order to enable visual feedback of the test rig's operation. This SCS can be implemented on any type of computer, however for economic reasons most types of available single-board computers on the market will be suitable for this application.

3. MECHANICAL DESIGN

a) *Linear motion modules*

The prismatic joints of the robot can be realized with linear motion modules, as shown in Figure 3. The structure of the linear module is a 40×80 mm aluminium (Al6060-T5) extrusion profile with T-slots. The T-slots of the profile enable easy and flexible mounting of various components which facilitate greater modularity in the design.

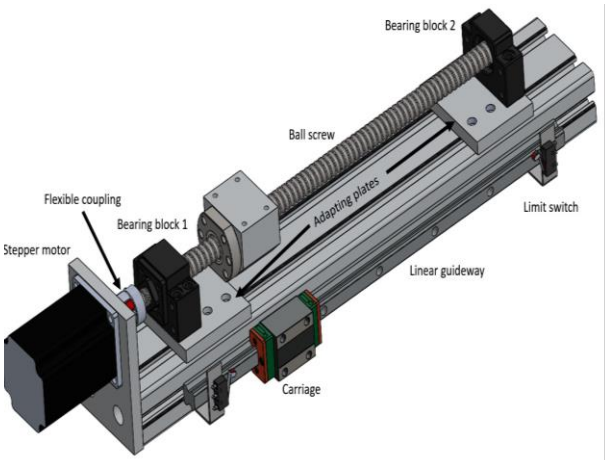

Fig. 3. *X* and *Y* axis linear module

In order to convert rotational motion of a motor into a linear one, a mechanical conversion mechanism is required. Considering the precision requirements of the test rig, a belt driven and ball screw driven motion were taken into consideration. As shown in Table 1 these two mechanisms demonstrate different properties in regards to precision, speed, backlash, etc. [22]. In the design of this test rig a priority was made on the precision and backlash properties when selecting a linear mechanism. Although belt drives can be very precise in light loads applications, such as in this case, nevertheless a ball screw was considered as a more suitable option.

Table 1

Comparison of ball screws and belt drives

	Ball screws	Belt drives
Thrust	High	Medium
Rigidity	High	Low
Speed	Low	High
Precision	High	Low
Noise	Medium	Medium
Backlash	Low	Medium

The ball screw is mounted on two bearing blocks which are fixated on the T-slots of the extrusion profile. Because the mounting holes of the bearing blocks did not match the T-slots' distance, it was required to add additional custom-made aluminium plates for proper fixation of the bearing blocks. In addition, a linear guideway is utilized in parallel with the ball screw in order to allow for motion and mutual fixture between the axes of the robot.

It was decided that a stepper motor shall be used as a motion actuator, being driven by an open-loop controller. The reason for this choice was because of its low cost and pervasive use in open-source projects. Open-loop stepper motors show disadvantages in motions demanding high accelerations or when driving heavy loads which demand the motor to operate close to its pull-out torque [20]. Such cases may cause the motor to loose steps which will lead to a situation where the controller can not determine its position anymore. The proposed test rig is not intended for driving heavy loads or executing high acceleration motions, therefore stepper motors appeared as a reasonable choice for this application. The motor size can be estimated through calculation of the required torque to drive the ball screw mechanism as [21]:

$$T_u = \frac{FL}{2\pi e} \quad (1)$$

where F is the axial force exerted on the ball screw mechanism in motion, L is the lead of the ball screw and e is its efficiency. This type of module was included in the design for the X and Y axes only. A similar approach was used in the design of Z-axes as well, shown in Figure 4. In order to avoid the full weight of an extrusion profile, like in X and Y axes linear modules, the Z axis' structural components include steel precision rods and custom-made aluminium parts. Since the stepper motor will drive the entire structure of the Z axis, it was crucial that weight reduction was considered in the design.

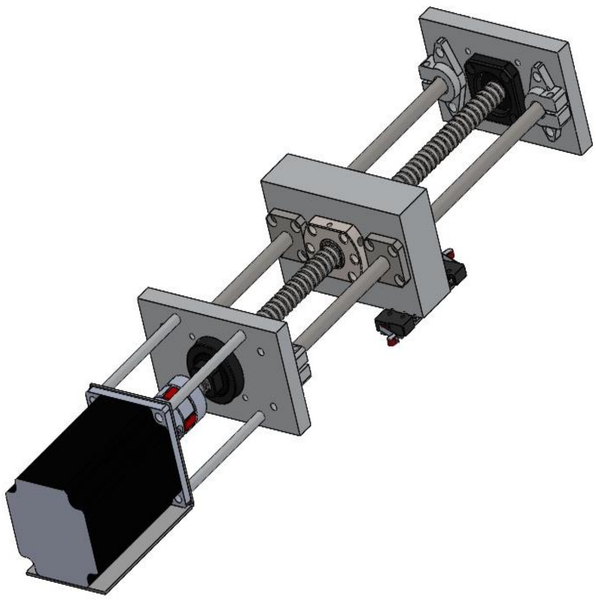

Fig. 4. *Z* axis linear module

b) *Rotary motion module*

In order to achieve a precise rotary motion for the rotor, a motorized rotary indexing table was implemented in the design. The indexing table utilizes a worm gear with high reduction ratio that enables precise rotary motion with high resolution. This indexing table will carry the rotor of the sensor and it is intended to be placed bellow the stator, which will be mounted on the Z axis of the robot. Figure 5 illustrates an example of this indexing table which will be driven by a stepper motor as well. This module will be incorporated as an independent additional axis in the MCS.

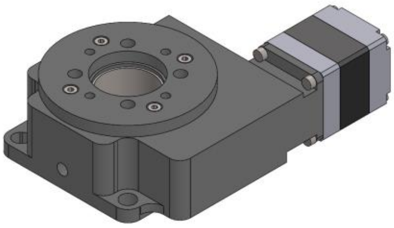

Fig. 5. Rotary indexing table intended for precise rotational motion of the sensor

c) *Robot structure*

The robot structure comprises of combination between 40×40 mm and 40×80 mm aluminium extrusion profiles as shown in Figure 6. The cuboid shape of the entire aluminium structure should provide sufficient rigidity for the robot. In addition, the robot is designed with dual *Y* axis containing two linear modules. Although this approach will potentially introduce the need of synchronization and alignment of the two linear modules, it was considered as a viable solution due to inaccessibility of rigid transmission hardware.

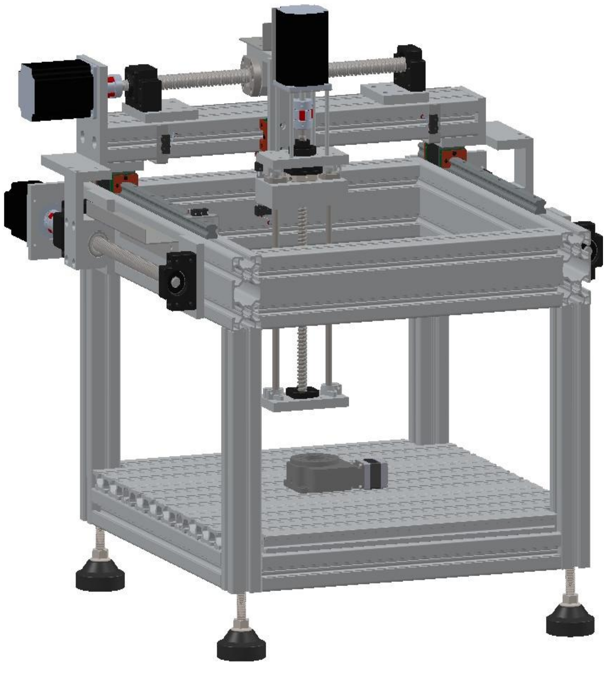

Fig. 6. Complete model of Cartesian robot

For accurate motion of the robot, its gantry should be assembled in a square shape where its dual *Y* axes are almost ideally parallel. For this purpose it is important that the extrusion profiles are precisely cut during procurement. This would allow to utilize *L*-shape connector joints, as shown in Figure 7, which should theoretically enable easy assembly in a precise square shape. This is of course mainly affected by the quality of manufactured *L*-shape connectors. This approach will ensure precise enough assembly and therefore omitting the need for further precision machining. In addition, the connectors shall be mounted in the *T*-slots of the extrusion profiles which will allow for supplementary flexibility and modularity during assembly process. The working table of the robot is comprised of 180×20 mm aluminium extrusion profiles with T-slots, which will ensure easy mounting of additional hardware components.

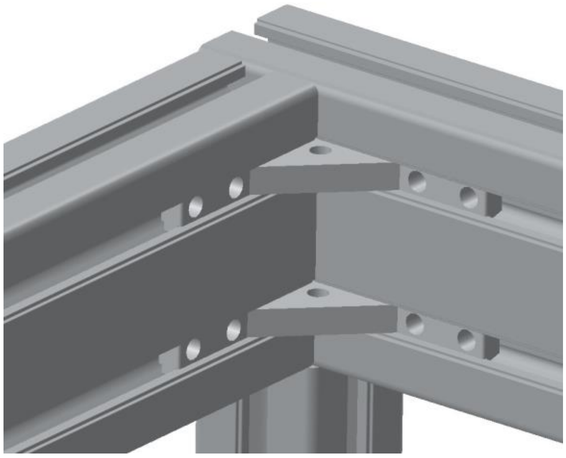

Fig. 7. Connection joints between extrusion profiles

d) *Robot structure*

Considering the decentralized multi-joint control nature of the robot, its forward and inverse kinematics is straightforward and can be easily obtained with the same expression. If it is taken that the reference coordinate system is placed in the origin of *X* and *Y* axes with a distance D_z from the *Z* axis prismatic joint, then the forward kinematics can be expressed as:

$$\begin{cases} x &= d_x \\ y &= d_y \\ z &= D_z - d_z \end{cases} \quad (2)$$

where (d_x, d_y, d_z) is the linear motion of each prismatic. Each linear motion within a linear module is result of converted rotary motion from the motor, which can be expressed as:

$$d = L\frac{\theta}{2\pi} \quad (3)$$

where L is the lead of the ball screw and θ is the rotational position of the motor. Consequently Eq. (2) can be rewritten as:

$$\begin{cases} x &= L_x \frac{\theta_x}{2\pi} \\ y &= L_y \frac{\theta_y}{2\pi} \\ z &= D_z - L_z \frac{\theta_z}{2\pi} \end{cases} \quad (4)$$

where (L_x, L_y, L_z) is the lead of the corresponding ball screw for each linear module and $(\theta_x, \theta_y, \theta_z)$ are the individual rotational positions of the motor.

4. ELECTRICAL AND SOFTWARE DESIGN

The electrical and software design details can be observed in Figure 8. The SCS hosts a web-based GUI software for monitoring and supervisory control activities with the test rig. The client can remotely access the GUI using web communication protocols through LAN or WAN. For security reasons, the remote access from WAN will be intermediated through a VPN service which will be hosted on the SCS. This approach should allow for secure remote connection to the test rig. The client can setup a concrete control strategy for the test rig through the SCS GUI. On the other hand, the SCS executes the control strategy by coordinating the motion of the robot and initiating the process of taking measurements from the oscilloscope. The SCS communicates with the oscilloscope through LAN, using Standard Commands for Programmable Instruments (SCPI), which is a commonly used command set in most commercial oscilloscopes [23]. The test rig can be observed through real time video stream accessed through the SCS software, obtained from a LAN connected camera.

Using USB communication, the MCS will receive the motion commands from the SCS and it will execute them respectively. Each axis stepper motor is driven by an individual motor driver which is controlled from the MCS. In order to achieve synchronized motion, the dual *Y* axis motor drivers will be connected to the same output signals, with the exception of "disable stepper motor" signal. The reason for this is to allow for automatic axis alignment once the axes have been aligned physically. In addition, each axis contains front and back limit switches for homing and protective activities. The *Y* 2-axes limit switches are only added for alignment purposes and therefore can be omitted in alternative design solutions.

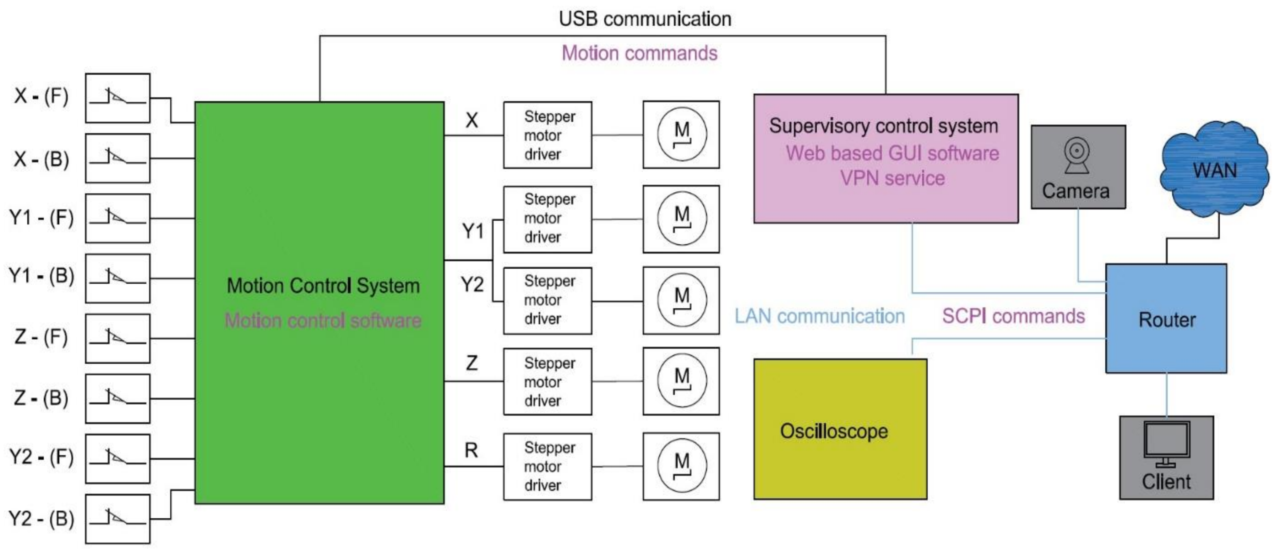

Fig. 8. System architecture with electrical and software details

5. CONCLUSION AND FUTURE WORK

A design solution for a test rig, intended for experimentation with angular position sensors, was proposed. Apart from rotational motion, this configuration allows for performing tests on the sensor through motion in Cartesian space as well. The motion of the robot and measurement triggering is coordinated from a supervisory control system (SCS) running software which allows for setup, monitoring and data acquisition. The SCS software is web-based and therefore allows for remote access through LAN or WAN which will also stream a real time video from the test rig. The mechanical design of the robot considers a modular and flexible approach in order to allow for easy repurposing of the robot for educational use. Apart from the mechanical design details, in regards to the Cartesian robot, the electrical and software details of the test rig were also shown.

In the future it is intended to perform a practical implementation of the design and test its applicability. The accuracy and repeatability of the robot should be measured in order to establish boundaries of the test rig. Any remarks and possible corrections during mechanical assembly should also be noted. A specific choice in regards to hardware components for the MCS and SCS should be made, along with appropriate software libraries for motion control, VPN service, SCPI communication, etc. A software implementation of the web-based GUI software should be realized along with its communication with the MCS and oscilloscope. Finally a general experimentation test on an angular position sensor should be made in order to establish the usability of the test rig.

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