CONTROL ELEMENTS OF A DELTA ROBOT LABORATORY MODEL

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ABSTRACT. The article presents control elements of a mechanism with parallel kinematics, known as a delta robot. Manipulators of this type are increasingly used in industry to solve tasks related to the high-precision manipulation of small details. This is due to the fact that the movable platform always remains parallel to the base, and the architecture has very low inertia which allows the realisation of fast and precise movements. Commercial solutions are high priced due to the precision mechanics, expensive drive systems, proprietary control electronics, and various patents. At the same time, the programming software is most often closed source. These problems hinder the intervention in the structure and algorithms of the mechatronic system. A laboratory model is proposed, which allows the demonstration and study of various components of the construction, drive, feedback, and control of the robotic platform, as well as the program implementation of various algorithms. The construction of the built mock-up allows for easy upgrading and can be used in multiple academic course units related to education in the field of mechatronics.

Key words: mechatronics, delta-robot, parallel kinematics, manipulator.

ЕЛЕМЕНТИ ОТ УПРАВЛЕНИЕТО НА ЛАБОРАТОРЕН МАКЕТ НА ДЕЛТА РОБОТ

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РЕЗЮМЕ. В статията са представени елементи от механизъм с паралелна кинематика, известен като делта робот. Манипулатори от този тип намират нарастващо приложение в индустрията за решаване на задачи, свързани с манипулацията на малки детайли с висока точност. Това се дължи на факта, че подвижната платформа винаги остава успоредна на основата, а архитектурата е с много ниска инерция и позволява реализирането на бързи и прецизни движения. Предлаганите на пазара решения имат висока цена, дължаща на прецизна механика, скъпи задвижващи системи, фирмена управляваща електроника и различни патенти, а обслужващият софтуер е най-често със затворен код. Тези проблеми възпрепятстват интервенцията в структурата и алгоритмите на мехатронната система. Предложен е лабораторен макет, който позволява демонстрирането и изследването на различни компоненти от конструкцията, задвижването, обратните връзки и управлението на роботизираната платформа, както и програмното реализиране на различни алгоритми. Конструкцията на изградения макет позволява лесно надграждане и може да намери приложение в различни учебни дисциплини, имащи отношение към обучението по мехатроника.

Ключови думи: мехатроника, делта-робот, паралелна кинематика, манипулатор.

Introduction

The parallel kinematics manipulator known as the delta robot was designed in the 1980s. It was created by a team at the École Polytechnique Fédérale de Lausanne (EPFL, Switzerland) under the direction of Professor Raymond Clavel, who later patented it (Clavel, 1990). The story began with a visit to a chocolate manufacturer (Hadfield, 2020), where he came up with the idea of making a machine to sort the candies into their boxes. The original purpose of the invented machine was to work in cyclic mode with small-sized, light-weight objects at very high speeds. Currently, robots with a similar kinematic structure are used in the electronic, food, pharmaceutical, and many other industries where the human factor can be eliminated in favour of achieving a high level of hygiene, increased productivity (Kostadinova, 2022), safety and high product standards. Parallel kinematics manipulators are extremely suitable for automating high-precision applications for which traditional robots or SCARA-type robots are inapplicable. With the burst development of digital computing equipment, the rising capabilities of power electronics, the augmenting demands for reliability, and the level of automation in industry, the applications of delta robots are ever increasing. A clear example of this is the fact that 3D printers with a parallel kinematic structure are now widely available to the mass consumer and are successfully used in the hobby industry. The research in the field is also continuing with increasing intensity. For example, in 2017 scientists from Harvard University in the United States created the smallest delta robot to date, "milliDelta", which is a micro-electromechanical system (MEMS) that has foldable piezoelectric actuators. It measures 15x15x20 mm and can move objects weighing 1.31 grams in an area of 7.01 mm^3 with an accuracy of 5 μm, reaching a speed of 0.45 m/s and an acceleration of 215 m/s^2 (McClintock, 2018).

This article presents the concept of building and controlling a manipulator with parallel kinematics. Although the delta robot model is currently not fully completed, the paper describes some basic nodes of the mechatronic system control. Various programming control approaches are also discussed.

Motivation of the research

Modern education in the field of engineering course units requires an interdisciplinary approach and the state-of-the-art technical equipment. Its combination with the conduct of practical experimental research is the only way to create professionals capable of meeting the needs of the market. This is an area in which practical experience is of utmost importance, as it helps not only to make sense of the complex of theoretical propositions, but guarantees practical skills and is a vital prerequisite for the formation of analytical and creative thinking. ~~Providing~~ Offering equipment of similar quality is still a serious challenge as it is associated with high financial costs (Fanuc, 2023; Omron, 2023) and training to work with closed-source software products. Despite the high quality of the hardware, such a solution does not provide the necessary flexibility in training and hides a wide range of low-level technical problems from the trainees. The listed reasons motivate the creation of a physical mock-up from scratch. This process aims to show that in fact the creation of a parallel kinematics manipulator is possible under much more affordable conditions, as well as to increase the quality of education in a wide range of engineering course units related to mechatronics.

Kinematic structure

The kinematic structure of the delta robot consists of a base on which three motors M1, M2, and M3 are mounted, which drive three arms (Fig. 1).

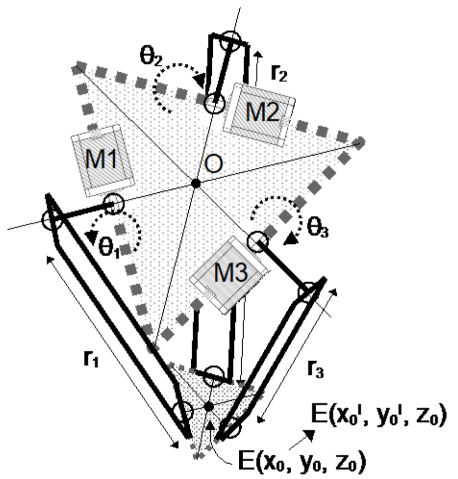


Fig. 1. Kinematic frame of the delta robot

A platform with center E(x_0, y_0, z_0) is connected to the arms by means of bearing joints and three parallelograms; this carries the working tool (end effector). The construction ensures that the platform of the tool will remain parallel to the work surface. The current delta robot has three translational degrees of freedom, although in Clavel's model there is also a fourth rotational degree that serves to rotate the tool.

Through appropriate control, the delta robot provides an opportunity to demonstrate the two main tasks of kinematics. The inverse kinematics problem allows the calculation of the required angular displacements for each of the three arms so as to provide a desired position of the work platform. The forward kinematics problem allows the position of the end effector to be determined if the angular positions of each of the three robot arms are known. The detailed solution of the kinematic equations falls beyond the scope of this paper, but it can only be said that to find the coordinates (x_0, y_0, z_0) one needs to solve a set of three equations of type (1) (Liu, 2019; Michalík, 2021):

$$\left(x-x_i\right)^2+\left(y-y_i\right)^2+\left(z-z_i\right)^2=r_e^2 \qquad (1)$$

In this equation, (x_i, y_i, z_i) are the coordinates of the center of the virtual sphere which describes the trajectory around the connection joint for each corresponding arm, and r_e is the radius of the sphere. The translation to a new end point can be obtained through trigonometric transformations (2).

$$\begin{aligned} x^I &= x.\cos(120)+y.\sin(120) \\ y^I &= -x.\sin(120)+y.\cos(120) \end{aligned} \qquad (2)$$

A situation may exist in which the working tool cannot move in certain directions or reach certain points in its working space, which is called the workspace singularity. In such areas, the delta robot can experience limitations in movement or can operate with reduced accuracy. The Jacobian matrix relates the speed of movement of the robot's joints to the speed of the end effector. When its determinant becomes zero, the robot falls into a kinematic singularity and loses mobility. For these reasons, the working area of the delta robot is often artificially constrained to spaces in which no singularity is observed.

Control system layout

The generalised control system layout of the proposed delta robot comprises a base control board and three stepper motors, as depicted in Fig. 2.

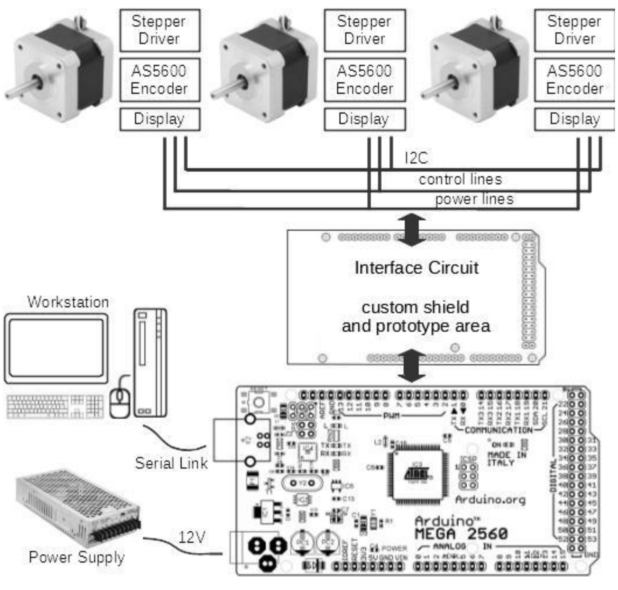


Fig. 2. The control system layout

In terms of hardware, the core of the systems is occupied by the Microchip 8-bit AVR RISC-based ATmega2560 microcontroller that is populated on the Arduino Mega board. It provides Inter-Inter-Circuit (I2C) and Serial Peripheral Interface (SPI) communication channels, has plenty of inputs and outputs (I/O), and is powerful enough to allow for experimenting with a broad amount of control algorithms. Nevertheless, an interface custom shield that fits on top of the main board has been designed in order to provide unified interface channels for the stepper driver boards. It includes the 12V power supply connectors, RJ-45 connectors for control signals, and a 74HCT4052 bidirectional dual single-pole quad-throw analog switch. The core of the circuit diagram is given in Fig. 3.

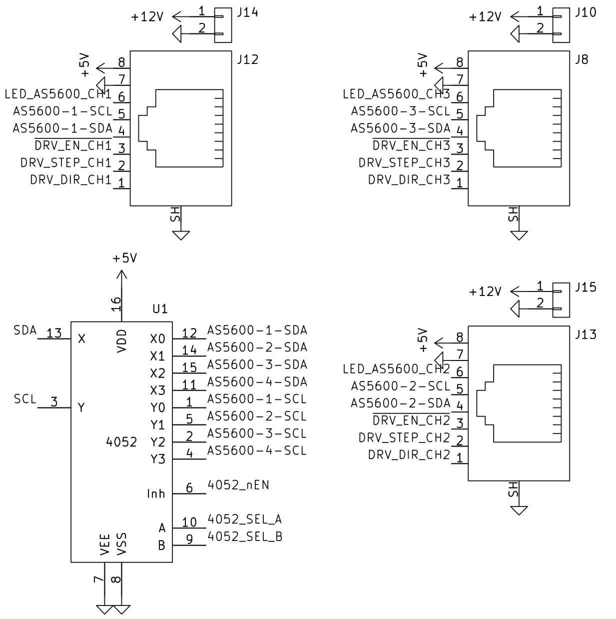


Fig. 3. Circuit diagram of the interface board shield

The use of the analog 4:1 multiplexer/demultiplexer is determined by the fact that the servo motor controller boards that connect to the shield contain an absolute magnetic encoder integrated circuit that uses the I2C bus but has a fixed slave address that cannot be configured. This problem has been solved by multiplexing the I2C signals which can be considered as a non-trivial solution for the I2C bus.

A 3D model of the designed printed circuit board (PCB) is shown in Fig. 4.

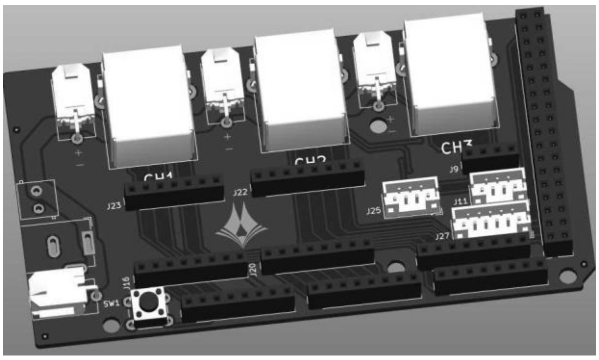


Fig. 4. 3D view of the PCB of the interface board shield

It can be seen from the design of the board that, if not counting the headers below the RJ-45 connectors, the shield keeps full compatibility with other extension boards that can be mounted on top of it. For example, it allows a large LCD display to be added, thus providing capabilities for self-contained autonomous use. All unused pins are also made available for future extensions.

The servo motor controller

The other essential component of the system is the servo motor controller. Most of the educational delta robots of this class, as well as most of the 3D printers that share similar kinematics, employ an open-circuit control topology the only benefit of which is its low price. Everything else, however, is considered being a drawback. The main reason for that is the fact that such systems are prone to skipping steps if the load is too high. Therefore, the best solution is to use a servo motor which provides inherent positional feedback. The conceptual block diagram is depicted in Fig 5.

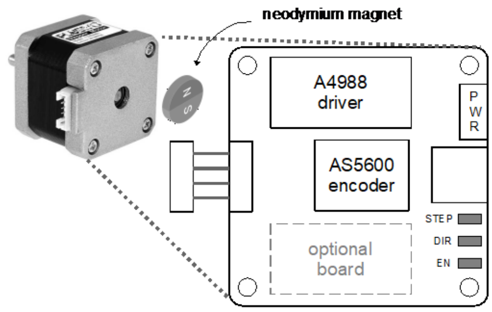


Fig. 5. Conceptual sketch of the motor controller

The motor controller board has the form factor that allows it to be mounted on the back of a standard NEMA 17 stepper motor measuring 42x42 mm. The present board contains the A4988 DMOS microstepping driver with translator and overcurrent protection but it has been designed in a way that supports several different motor drivers mounted on a socket. A brief comparison of compatible drivers is given in Table 1.

Table 1. *Compatible stepper motor drivers*

Model	Stepping	U [V]/I [A]	Price
Allegro A4988 	full, 1/2, 1/4, 1/8, 1/16	8-35V 2A	1.80 USD
TI DRV8825 	full, 1/2, 1/4, 1/8, 1/16, 1/32	8.2-45V 2.5A	2.20 USD
Trinamic TMC2225 	Up to 1/256	4.7-36V 2.5A	6.00 USD
ONsemi LV8729 	Up to 1/128	6-36V 1.3A	6.75 USD

Although in the present version the basic A4988 stepper motor driver by Allegro has the best price/performance ratio, several other driver modules exist that support microstepping control with step division of up to 1 over 256. They are more precise and behave more quietly, but at a greater price. The drivers from Trinamic Ltd., a motion control leader that was acquired in 2021 by Analog Devices, might be particularly well-suited for future applications.

The motor controller board is equipped with a 12-bit on-axis magnetic rotary position sensor with analog and Pulse Width Modulated (PWM) output AS5600 by AMS. It is a Hall-based contactless rotary absolute encoder with a resolution of 4096 distinct sectors which equates to 0.088 degrees per sector. The chip is mounted on the opposite side at the center of the controller board. A radially magnetised neodymium magnet which is coaxial with the sensor is mounted on the motor axis. The working principle of the position detection using magnetic field (AS5600, 2018) is illustrated in Fig. 6.

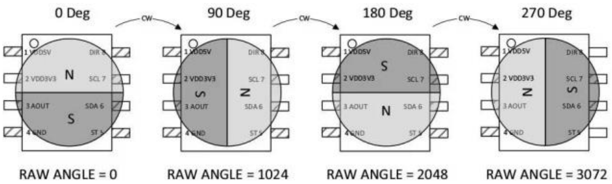


Fig. 6. Working principle of the AS5600 position detection

The AS5600 sensor has hysteresis control (avoids toggling the output when the magnet is not moving), magnet detection, watchdog timer to save power, and high resolution which makes it a fairly reliable device.

The circuit diagram of the servo motor controller board is shown in Fig.7.

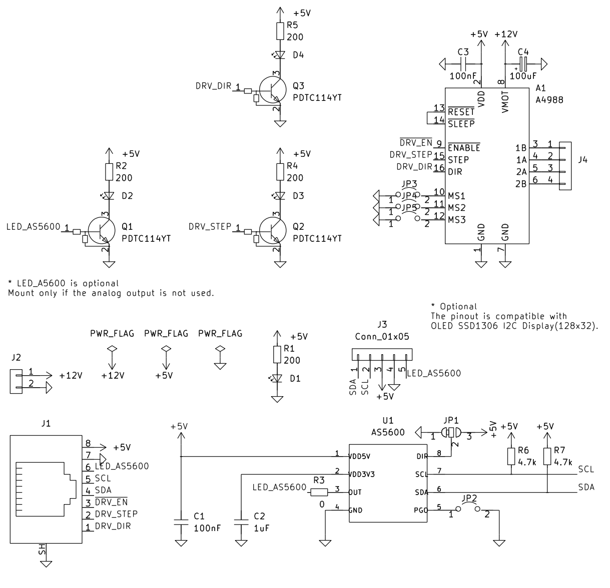
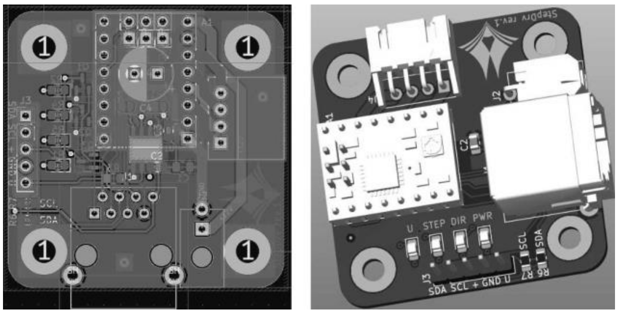


Fig. 7. Circuit diagram of the servo motor controller board

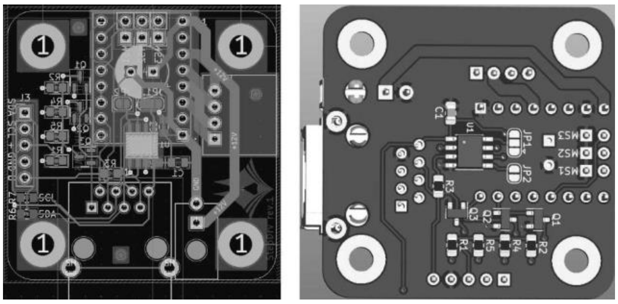
The circuit comprises the AS5600 absolute encoder, the driver circuitry, four LED indicators, the RJ-45 plus power supply connectors, and the J3 expansion connector which allows to connect an I2C OLED display module.

The model of the designed printed circuit board (PCB) is shown in Fig. 8 – top side with the stepper driver, and Fig. 9 – bottom side with the magnetic encoder integrated circuit.



(a) (b)

Fig. 8. PCB design (a) and 3D view (b) of board’s top side



(a) (b)

Fig. 9. PCB design (a) and 3D view (b) of board’s bottom side

The OLED display is optional and is not shown in the figure. The design of this board allows to offload the extension shield from the stepper motor drivers which improves the noise immunity of the system. It also makes the electrical drive subsystem of the delta robot highly modular.

Control methods

Open-loop control

The most common control method that is being used in mechatronic systems with parallel kinematics is the open-loop control. In this method, the stepper motors are controlled by feeding them with step and direction signals without providing feedback on current position. Due to the nature of the stepping control and the relatively large holding torque of the motor, the set steps are considered to have been worked. For control to be universal, geometric codes (G-Code) are most often used. G-Code is the de-facto standard programming language for CNC (Computer Numerical Control) machines and is widely adopted by the industry. The command line format for the G-Code is (3):

G## X## Y## Z## F## (3)

The G-code command determines the type of movement. It can be rapid positioning (G00), linear interpolation (G01), clockwise (G02), or anticlockwise (G03) circular interpolation, units selection (G20 – inches, G21 – centimeters), homing (G28), or other code (Oberg, 1996; S). The G-command is followed by the X, Y, and Z coordinates followed by the feed rate F. The G-Code specification is given by the RS-274 standard (Kramer, 2000). The use of G-Code with the Arduino platform is made possible with the aid of the free open-source motion control GRBL interpreter firmware (Sarguroh, 2018) shown in Fig. 10.

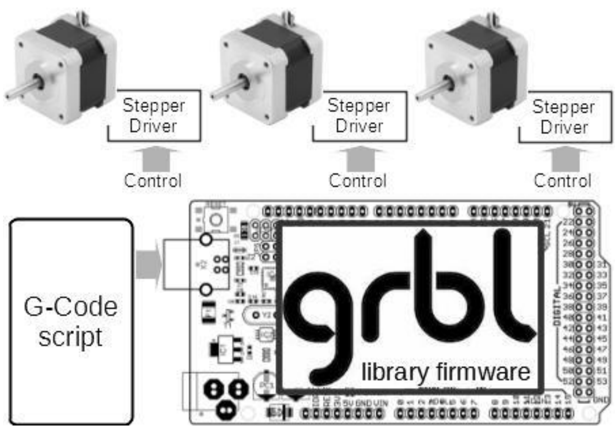


Fig. 10. The GRBL open-loop control

The G-Code script can be easily prepared with the help of a CAD (Computer-Aided Design) software, as most of these programs can export into the G-Code format.

This approach gained popularity due to its simplicity and accessibility but the lack of positional feedback remains a serious drawback.

Control with a teacher

Since the proposed delta robot can provide positional feedback, another approach is the control with a teacher. This presumes that when the motors are disengaged (i.e. lack of control), a human operator can step into the role of a teacher and guide the working tool along a desired trajectory thus "training" the robot. Thanks to the feedback, after completing the training, the robot can repeat the execution of the memorised path.

Custom control

The proposed manipulator with a parallel kinematic structure enables the exploration of a broad range of control algorithms created by the user. For example, it is not difficult to implement control using a joystick with visual feedback. Also, real-time computer control can be implemented based on complex algorithms implemented with a mathematical product such as the Matlab commercial package or its free analogues SciLab and QT Octave. These approaches are the subject of our future work.

Conclusions

The use of parallel kinematics manipulators in industry is gaining a constantly growing popularity, but commercial solutions are not yet readily available for training purposes, mainly due to their high price and closed-source control software. The article deals with the design of the main nodes of the control of a mechatronic system known as a delta robot, which makes it possible to conduct physical experiments and research in solving the direct and inverse task of kinematics, study of dynamic behavior, and the design of a wide range of control algorithms. The proposed manipulator allows for easy upgrading and can be used in various academic disciplines related to mechatronics training.

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