CONTROL SYSTEM OF THE ARTICULATED ARM BRAKING MECHATRONIC MACHINE (AABMM)

Mikhail Solovyev, Vorotnikov Andrei, Daniil Klimov,
Kovalskii Vladislav, Yuri Poduraev

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Abstract

An approach to solving the problem of fixing objects in space with a given position and orientation is considered in the article. The concept of the Articulated Arm Braking Mechatronic Machine (AABMM) is described, which allows solving this problem in various fields of science and technology. The synthesis of the control system based on modular approach has been carried out. A rig for testing and calibration of sensors, designed to improve the reliability of the system and the accuracy of the feedback loop elements was developed. The proposed control system will allow to operate the AABMM with different kinematic structures and function sets.

Keywords: control system; medical robotics; mechatronic; sensor calibration; articulated arm

1. Introduction

In various areas of human activity, there are tasks that require fixing objects in space with a given position and orientation, relative to other objects. Similar problems can be found in industry, where it is required to keep the workpiece or tool in a certain position during processing, or in cinematography, to position the imaging equipment during process shooting for alignment with 3D-graphics [1]. A wide class of similar problems can be found in medicine. For example, in neurosurgery, when performing operations in the region of the spinal cord or brain, it is necessary to fix the position of the medical instruments relative to the operating field for their further accurate surgical insertion into the living tissue of the patient. Precise positioning of the instruments at the time of the medical operation reduces the risks caused by the human factor, ensures a low invasiveness of the intervention, increases the speed of the operation. To effectively solve these problems, the concept of a mechatronic device – Articulated Arm Braking Mechatronic Machine (AABMM) is proposed, consisting of a series of links capable of fixing relative to each other in a certain position necessary for the user, with built-in brakes. A similar approach to the solution of these problems in the field of medicine is considered in [2,3], however, despite the close solution in link fixing, there are no positioning devices provided, so the navigation of the medical instrument is done manually.

In the RSSS (Robotic Spinal Surgical System) system described in [4,5], it is proposed to use a manipulator capable of working in a collaborative mode, allowing the individual links to move manually, which makes it functionally close to the AABMM. Nevertheless, the problem of navigation in RSSS is solved on the basis of stereo photogrammetry, using an external stationary stereo camera and markers on the end effector of the manipulator. In AABMM, in turn, precise angular sensors are used to determine the position, thus allowing navigation without external measuring equipment.

The aim of the work is to cover the problems of design and development of the electronic subsystem of the AABMM, including low-level software. The paper considers the synthesis of the structure of the modular control system of the mechatronic device, the approaches to transferring and receiving information between the elements of this structure, as well as the development of the rig and experimental studies for testing and calibration of absolute position sensors - an essential element of AABMM.

2. Description of the kinematics and internal components of the AABMM

The developed mechatronic device is an articulated arm of the open kinematic model. Inside of the joints of the kinematic pairs, precision angular position sensors and brake devices are located. The structure of the kinematic scheme, the number and the size of the links can vary depending on the requirements of operation. The general view of the AABMM (Articulated Arm Braking Mechatronic Machine) is shown in Figure 1. The main function of this device is to limit the movements of the end effector to perform the tasks assigned. When performing an operation, the brake devices fix the articulated arm and does not allow the end effector to deviate from the preset position.

The position and orientation of the end effector is specified to the AABMM in the control program, as a set of lines of code necessary for execution. After loading the control program, the control system, in which the kinematic model is set, reports the necessary moving commands to the user. The movement of the end effector from one position to another takes place manually and can be done in two ways: by moving around or along each selected axis to the specified position one by one, or by manually moving the articulated arm to the desired position, and then fixing all the joints. The braking devices can be switched on and off by means of control elements located on the AABMM body.

Fig. 1. Kinematic models of typical AABMM

The basis of the mathematical description of AABMM in the control system is the direct kinematic problem. The solution of the direct kinematics problem allows to transform the space of generalized coordinates of the position of the AABMM joints into the Cartesian space by means of several transitions from the previous link to the next one. Each transition is carried out in accordance with certain rules established by Denavite and Hartenberg [6] and is described by a homogeneous transformation matrix of 4 by 4 dimensions:

$$A_i^{i-1} = Trans(z_i, d_i) \cdot Rot(z_i, \theta_i) \cdot Trans(x_i, a_i) \cdot Rot(x_i, \alpha_i) \quad (1)$$

where $Trans(h_i, \chi_i)$ and $Rot(h_i, \chi_i)$ – homogeneous transfer and rotation transformation matrices, respectively, h_i – rotation or transfer axis (x_i , y_i or z_i) i coordinate systems, χ_i – angle of rotation or length of transfer i coordinate system to one of the geometric parameters: d_i , θ_i , a_i , α_i . The number of matrices corresponds to the number of joints in the mechanism.

For the developed kinematic model, it is necessary to perform a calibration by determining the actual values of the geometric parameters (d_i , θ_i , a_i , α_i): displacements of generalized coordinates (initial relative position of links), real lengths of links and displacements between them. Calibration of AABMM is possible to perform in a variety of approaches, for example, using:

- Identification of all geometric parameters of the kinematic model of the control system. For this purpose, the coordinates of the points of the position of the working element, measured throughout the entire working area of the AABMM, are approximated.
- Definition of individual geometric elements of the robot using CPA (circle point analysis) and further transformation of the entire kinematic model.

A more detailed description of these approaches was proposed in [Error! Reference source not found.- Error! Reference source not found.].

3. Modular control system of the AABMM.

When designing the control system for AABMM, a modular approach was used [10]. This approach consists in combining devices for various purposes into a constructively and functionally independent product. For AABMM, it is rational to combine the sensor and the brake in each joint into a separate module. All modules include a unified control board. In this board, feedback is created by means of a high-frequency survey of absolute angular position sensors and, in accordance with the specified program or an external command from other modules, interaction with the control object (brake) occurs.

The generalized AABMM block diagram, using the modular principle, is shown in Figure 2. The communication between modules is carried out using a single data bus (DATA BUS). All modules (Slave module) interact with control objects in the joints. This approach allows you to distribute the computational load by high-frequency data processing from the sensors parallel between each module, which leads to an increase in the processing speed. It also makes it possible to change the number of joints in AABMM without any additional changes in the control system. In addition, with this approach, the production of identical modules for AABMM becomes more economically feasible [10]. The control system uses a master module to interact with an external PC via Ethernet protocols, which manages the system by sending commands and monitoring the position of the links by surveying the slave modules.

Fig. 2. Generalized block diagram of the AABMM control system

A data bus I2C was used to connect the modules. This choice is due to two criteria: a small number of wires and the simplicity of the data exchange protocol, compared to other bi-directional buses. A small number of wires allows the use of an angular position sensor with a hollow shaft, which has a small diameter, which makes it possible to reduce the dimensions of the structure. The choice of I2C as the data exchange protocol was made to simplify the development of additional modules. This bus is present in most controllers and processors, which allows you to create additional modules through software modification of the connected devices. The development of modules for finite devices is reduced to designing an adapter between the control interface and the data bus. As additional modules are considered specialized end effectors, fixed on the flange. It is also possible to use information devices that transmit patient data during the

operation or the parameters of the working environment directly by the flange. There are 7 modules for joint management and 6 additional modules for connection of end effectors.

During the development of the control system, two changes were made to the data bus. The first change is to increase the voltage on the two power wires. The voltage value was increased from 5 volts to 12. This is due to the need for increased supply of brake components in the module. The second change is related to the data rate on the bus clock and data bus. From the "classic" standard value of 100 Kbits / s, it was increased to another speed value of 400 Kbits / s. This is due to the provision of a time reserve for data transmission in case of a critical situation, for example, stopping of the operation of all modules by the PC command.

In addition to the implemented method of instant brake locking in all modules, in response to a specialized signal, it is possible to transmit an emergency command sequentially to each module. The time for such a transmission should not exceed the button contact jitter processing time of 0.01 seconds. Although the maximum design response time of the system is 0.0026 seconds, under operating conditions, data and data processing errors are possible, so the speed has been increased with a safety factor of 4. Thus, a balance was observed between the number of wires and the speed of the system, depending on the data transfer rate on the bus.

Let us consider the structure and operation of the modules in more detail. A detailed block diagram is shown in Figure 4. The slave module (Figure 4a) produces high-frequency data reading from the position sensor. The data is written to the ring buffer of the device and, when requested via the data bus, it can return both the last recorded value and the entire buffer. Brake control in the module occurs in accordance with the program or commands received via the data bus. The module's functionality allows you to enable or disable the brake depending on the angle of relative position of the links in the joint, from the command on the data bus or from the command of the control on the housing, such as a button. As a controller, the AVR ATMEGA328P microcontroller is used.

The I2C interface module of the microcontroller is directly connected to the common data bus. The slave module has three control elements: a brake, a sensor and a control board mounted on the body. The brake is connected to the board via a galvanic isolation using a relay. This is due to the difference in the brake control voltage and the operating voltage of the microcontroller. A power converter is used to power the entire system, which provides 12 volts for controlling the magnet and 5 volts for powering the controller and sensor. The absolute position sensor is connected to the controller via the RS-422 / RS-485 signal converter.

The task of the master module (Figure 4 b) is to control the system by sending commands and monitoring the position of the links by low-frequency surveying of slave devices. In addition, it communicates with an external control device, a personal computer through the physical network interface rj45 over TCP / IP protocols.

Fig. 4. Slave (a) and master (b) devices.

In the master module, the microcontroller as well as in the slave is directly connected to the data bus. The controller is connected to the PC by the ENC28J60 chip, which is an Ethernet controller designed to work with connections based on the 10BASE-T family interfaces. Control of this chip is carried out using the SPI protocol. For connection to a personal computer, a connector is used for the rj45 interface of the magjack type.

The master module is the master on the data bus. It initiates the reception and transmission of data with slave modules. Thus, there is no possibility of overlaying information from two different modules. This implementation allows the use of basic TCP / IP protocol tools to communicate with the device and interpret data in any certified software [11], which is designed to work with a medical device.

4. Testing and calibration rig for absolute position sensors.

It is possible to use AABMM in medical practice to perform operations on a patient. Therefore, the measuring devices used in medical AABMM should have increased requirements for accuracy and reliability. As measuring devices for AABMM, it is advisable to use absolute position sensors, which, unlike incremental sensors, save information about the current position when the power is turned off. Absolute position sensors are installed in the joints and allow to determine the position of the next link relative to the previous one. In connection with the increased requirements for absolute position sensors, it is necessary to evaluate their accuracy against the manufacturer's specified qualitative characteristics.

A specialized rig has been developed for the testing of angle sensors. Its principle of operation is to test a less accurate sensor using a different, more accurate one. Both sensors are fixed to a single shaft, which moves to an angular discrete smaller than the accuracy of the sensor being tested. For each discrete value is read from the two sensors, which are recorded in a look up table. Values of the look up table for full shaft rotation are used to determine the actual characteristics of the sensor being tested. With the help of such a specialized rig, it is also possible to calibrate the sensors, increasing their accuracy. The appearance of the stand is shown in Figure 5. It combines two sensors through a single shaft, the rotation of which provides a stepper motor through a worm gearbox. To reduce the initial value of the eccentricity and the relative inclination of the sensors, they are located at a minimum distance from each other. In this case, the design of the rig is designed in such a way, that it makes it possible to replace the tested absolute sensors without disassembly.

Fig. 5. Experimental rig for testing and calibration of sensors

The block diagram of the developed rig for testing absolute sensors is shown in Figure 6. The stepper motor with a worm gear is used as the device for creating the angular movement of the shaft. The stepper motor is controlled by a driver with the ability to generate a microstep. Microstepping allows you to "divide" the steps of the motor, thereby reducing the discretion of moving the common shaft. The microstep selection is carried out in accordance with the following formula:

$$k_{microstep} > \frac{360 * 60 * 60}{n_{step} * i_{reducer} * s_{sensor}} = 16.2 \quad (2)$$

where: n_{step} - the number of discretized steps of the stepping motor, $i_{reducer}$ - gear ratio, s_{sensor} - the resolution value per second. Since the driver uses coefficients equal to powers of 2, the microstep coefficient is assumed equal to 32.

As a controller for the test rig and calibration of sensors, a single-board computer Tion-pro270 was used. This computer has a large number of GPIO ports. With their help, the driver of the stepper motor is controlled by the STEP/DIR/ENABLE protocol. The shaft rotation is measured using a calibrated (LIRDA237T) and a reference sensor (ROD800).

Fig. 6. Structural electrical diagram of the rig for testing and calibration of sensors

The sensors used differ not only in their accuracy and resolution, but also in the way they deliver data. Comparison of the characteristics of the sensors is presented in Table 1. LIRDA237T, is an absolute encoder with a hollow shaft and having 2097152 discrete per revolution. It is this model that is used in all slave modules AABMM. The data from the sensor is read from the slave module, which is connected to the control board of the single-board computer via the I2C data bus. The reference sensor has a higher resolving power and accuracy. Since it is an incremental encoder with a sine-cosine signal, the position information is obtained by means of a sinus-cosine converter LIR960. This converter is connected with tion-pro270 via a dedicated asynchronous data bus.

	LIRDA237T	ROD800
Type	Absolute	Incremental
Resolution	5''	2''
Accuracy	30''	2''
Signal type	SSI	SINCOS

Table 1. Comparison of the characteristics of the sensors

For the manager of a single-board computer operating on the basis of the Linux operating system, a control program via the TFT screen was implemented. As a development environment, a cross-platform framework was used to develop Qt creator software. The complexity of the management program implementation is associated with the critical influence of each thread, on the duration of the calibration process. The solution to this problem is to divide the program into several threads. The number of streams was minimized, thereby facilitating the load on the computing power of the board. By setting thread priorities in a multithreaded system, all time delays were minimized. A simplified diagram of the distribution of threads in the program is shown in Figure 7.

Three threads are distinguished. Draw tread is designed to display the graphic interface on the TFT screen and to read the touch data to the capacitive matrix. Since the draw tread occupies a large resource of computing power, a low priority is set for the stability of the entire system and an increase in the calibration speed of a single sensor for this thread. The data thread from the asynchronous bus is only started when there is a command from the thread. The read function is based on writing the value to the ring buffer, which is located directly in the hardware of the bus. Thus, when the buffer overflows, a critical error will be created and the process of reading the data will need to be interrupted. Therefore, it is critically important to continuously parse the parcels from the asynchronous bus.

To stabilize the system, this thread was given the highest priority. For the main thread running linearly, high priority is set. In it, after the activation of the read command, the values coming from the two sensors are processed, the stepper motor is controlled via the galvanic isolation keys and the calculation of the traversed paths. Also, the function of saving data to the internal memory of the device or to a flash drive was realized.

Fig. 7. Thread diagram.

To fully compensate the eccentricity and the mutual tilt of the two sensors, an algorithm for processing the look up table was implemented. After obtaining a look up table between the data coming from the calibrated sensor and the reference sensor data, the signal is processed. The processing consists in the formation of an error signal of the sensor readings (blue graph). Next, a direct Fourier transform for the error signal and a transition to the frequency domain are performed. The first two harmonics create a compensating error signal and perform its inverse transformation from the frequency domain to the time domain (red graph). By subtracting the compensating error signal from the original signal, the eccentricity and mutual tilt of the two sensors are compensated and a look up table is created (green graph). Calibration is carried out by transferring table values to the memory of the module working with the calibrated sensor. The signal graphs are shown in Figure 8.

Fig. 8. Graphs of received sensor signals during calibration.

5. Conclusion

The article considered the problem of developing devices for fixing objects in space with a given position and orientation. In particular, a solution for the electronic control subsystem is proposed. The solution is based on the modular principle, which allows to combine control objects in the joints into functionally independent devices connected by a single data bus. In this way, it is possible to easily modify the lengths of the links, the number of joints and the device functionality by developing additional modules. This makes this type of device applicable for various classes of tasks, including operations in medical practice. Solutions for the electronic subsystem are described, structural and schematic diagrams and low-level software were developed. An approach to testing and calibrating the sensors of the modules is also described. The proposed solution in the form of a specialized sensor calibration rig is aimed at automating the processes of data acquisition, processing and analysis. Based on the described developments, it is planned to create a prototype of the AABMM, for use in medical practice.

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