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CNC machine laboratory stand with H-Bot parallel kinematics using the EtherCAT bus[3]

Summary

This paper presents an H-Bot kinematics machine control system. The H-Bot machine accuracy depends on the servo drives' synchronous operation and mechanical design. Therefore, the mechanical axes' movement quality is influenced by the communication bus and the ability to detect backlash and elasticity in the machine axes. EtherCAT – an industrial bus will be used for communication between the controller and other machine control system elements. Each mechanical axis at the H-Bot machine is equipped with a position measurement system. The laboratory stand was equipped with accelerometers. It is planned to perform research in the Predictive Maintenance and Trajectory Optimization field.

Keywords: H-Bot machine, machine control system, EtherCAT, LinuxCNC

1. INTRODUCTION

The positioning accuracy in machines with H-Bot kinematics depends on the machine's mechanical structure and the CNC machine's control system. In this system, a CNC controller in which calculations related to parallel kinematics is presented. The accuracy of the H-Bot machine depends on the synchronous operation of servo drives. Therefore, the quality of synchronous movement of mechanical axes is influenced by the communication bus (synchronous data exchange between the drives and the CNC controller).

The article (chapter 2) will discuss the basics of parallel kinematics for machines with an H-Bot design. The third chapter will discuss the design of the H-Bot machine used and the developed CNC numerical control system based on a PC and LinuxCNC software. This chapter will also address issues related to the EtherCAT communication interface of the CNC controller. Three different configurations of this interface developed by the article's authors will be discussed. In the chapter on research, the results on the quality of work of the developed EtherCAT communication interfaces will be presented and discussed.

2. KINEMATICS OF H-BOT MACHINES

In machines with the H-Bot design (Figure 1), there are two parallel tracks along which a linear bridge with bearings is routed. A third track is mounted on the bridge, perpendicular to the first two tracks on which the trolley is located. Three linear motion units form a structure similar to the letter "H" (hence H-Bot). At each end on two parallel tracks, there is one pulley. At two ends of parallel units, the pulleys are directly attached to the shafts of the engines. Four blocks are mounted on the bridge – two at each end. The toothed belt on the H-Bot machine passes through all eight pulleys. The belt ends are assembled to the trolley on the bridge. The kinematic system of a machine is not open kinematics. In the H-Bot design, rotary motors are mounted stationary. The proper movement of these motors allows the entire bridge to move along the x-axis and the cart itself on the bridge along the y-axis. Finally, the combination of these two linear movements allows the movement of the final effector.

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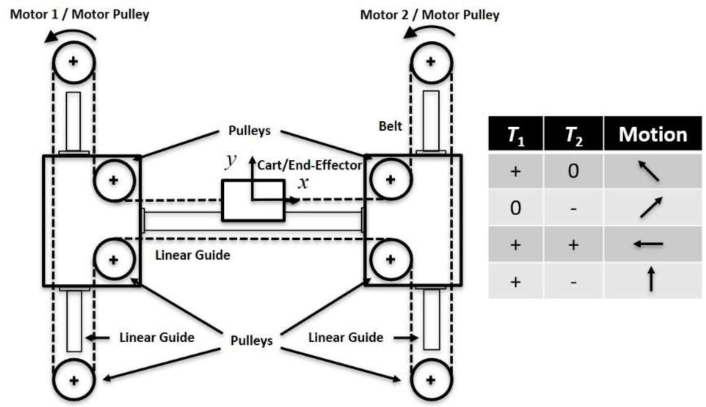

Figure 1. *Diagram of H-Bot type construction*

The rotation of the shaft of motor 1 with motor 2 stopped causes a linear movement of the effector at an angle of ±45° towards the XY coordinate system. Right rotation to the shaft of motor 2 with motor 1 stopped causes movement in positive directions of x and y axes. In contrast, rotation to the left of the same motor would cause movement in the negative direction of y and x. Mathematically, this can be written as:

$$r\Delta\varphi_1 = \Delta x - \Delta y \tag{1}$$

where r is the radius of the motor pulley and Δx, Δy is the change in the x and y axes position, and $\Delta\varphi_1$ is the resultant change in motor position.

Similarly, turning motor 1 to the right while stopping the shaft of motor 2 will cause movement in the positive x direction and the negative direction in the y direction, while the left rotation of the same motor would cause movement in the positive y direction and the negative x direction. Mathematically, this can be written as:

$$r\Delta\varphi_2 = -\Delta x - \Delta y \tag{2}$$

Solving equations (1) and (2) will result in the corresponding relationship for Δx and Δy:

$$\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix} = \begin{bmatrix}-\frac{1}{2}r & \frac{1}{2}r\\ -\frac{1}{2}r & -\frac{1}{2}r\end{bmatrix}\begin{bmatrix}\Delta\varphi_1\\ \Delta\varphi_2\end{bmatrix} \tag{3}$$

To build a dynamic machine model, assign generalized coordinates must be assigned. It can be assumed that the pulleys are as springs, so all pulleys are allowed to rotate freely apart to some extent. In the work of Sollmann et al. [1], he developed a twentieth-order model with cumulative parameters of the H-Bot design. Due to the large order of the model and the resulting computational problems in the simulation of this model, the same authors, in their next work [2], simplify the model by grouping some elements of this model. Finally, he managed to get an eighth-order model. Excellent compliance of the model with the data collected from the test stand has been shown.

The authors of this article plan to conduct research in the future to develop such a model of the H-Bot structure.

3. H-BOT MACHINE WITH LINUXCNC BASED CONTROL SYSTEM

The photo of the laboratory stand with the H-Bot machine is shown in Figure 2. The range of movement of the machine is 2m along the y-axis and 1m along the x-axis. The motors used in the machine are Delta Electronics PMSM motors with a rated torque of 1.5Nm and a nominal speed of 3000 rpm. The motors are equipped with absolute rotary encoders with 24-bit resolution. The gear ratio of the motor is 5:1. PMSM motors are connected to ASD-A3-E drives from Delta Electronics. Each axis has a linear encoder with a resolution of 1µm. All components are connected to the CNC controller via the EtherCAT communication bus [3].

Figure 2. *Photo of the stand with the H-Bot machine*

2.1 H-Bot CNC control system

The used control system [4] consists of a PC (with a real-time system based on Linux), two servo drives, auxiliary devices such as I/O modules, and linear encoders measuring modules. All components of the control system communicate with each other via the EtherCAT bus. Figure 3 shows a block diagram of the control system.

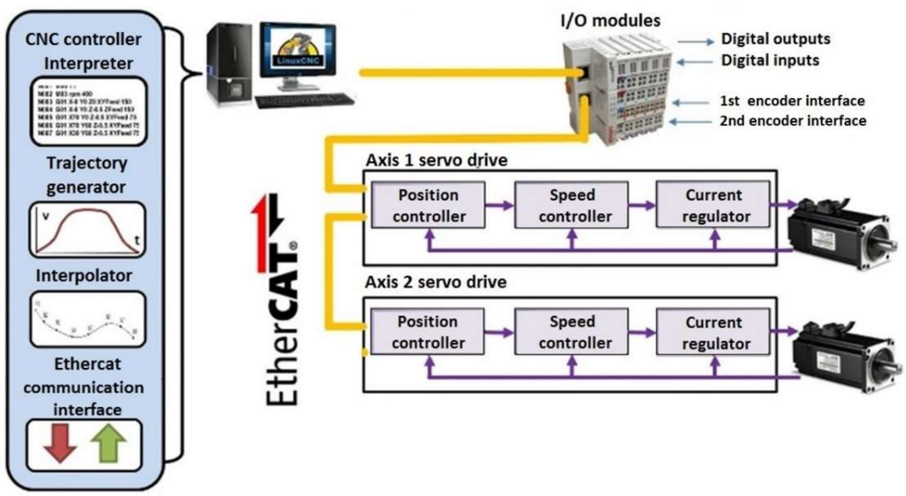

Figure 3. *H-Bot CNC control system*

The CNC controller is a desktop computer with an Intel Core i3 processor and an SSD drive. LinuxCNC was used as the control software, in which numerically controlled and kinematic transformations for the H-Bot system was implemented. All slave devices of the controller (drives, I/O, encoder interfaces) are supported by the Ethernet interface - EtherCAT bus. The PC controller communicates with 2 servo drives, an I/O module, and linear encoder modules cyclically (in cycles of 1ms, 500µs, or 250µs - depending on the settings).

The LinuxCNC control software on the PC uses the Linux RT-Preempt [5] real-time operating system, which enables deterministic execution of time-critical tasks. The main tasks of the controller are motion control and real-time communication via EtherCAT. Linux RT-Preempt is based on the standard version of the Linux kernel, which has been modified by installing an additional "system patch" RT-Preempt. Such modification enables the handling of all recurring tasks in real-time. All non-critical and real-time tasks are handled by the Linux kernel, with the difference that the last ones always have priority in handling (they have higher priorities than standard system tasks). Priorities also apply to hardware interrupts so that non-real-time drivers do not interfere with real-time tasks. Real-time and non-real-time timing tasks can be assigned to different processor cores to improve performance.

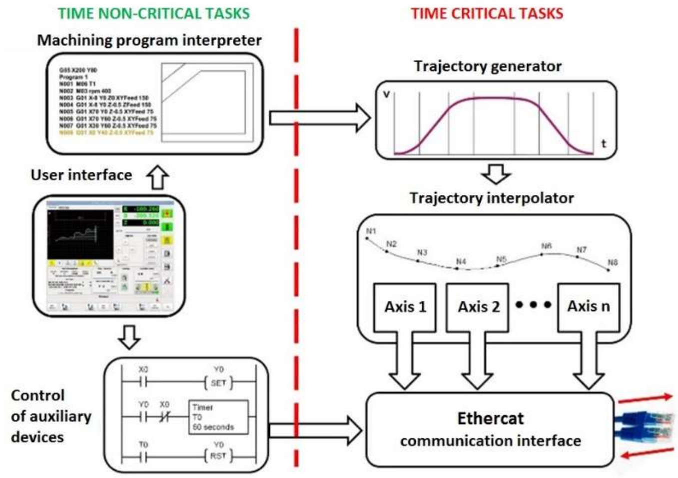

Figure 4. *Non-critical and deterministic tasks in CNC application.*

Figure 4 shows a block diagram of LinuxCNC real-time and non-real-time tasks. Non-real-time tasks include software modules like Graphical User Interface (GUI), G-Code interpreter [6], and peripheral handling devices. Real-time tasks are handled in the HAL hardware space as dedicated modules. The standard HAL modules include the *Motion* control module, which consists of a trajectory generator with trapezoidal acceleration profiling and an interpolator. H-Bot transformation kinematic module and EtherCAT communication interface module is also implemented there.

2.2 EtherCAT communication interface

To connect slave devices (servo drives and I/O modules) in LinuxCNC via EtherCAT buses, the authors had to implement a non-standard communication interface module. This module contains the EtherCAT standard communication stack, which implements the CANopen standard in the application layer according to the OSI model. An additional standard, CiA402, has been developed to control Delta Electronics ASD-A2-E servo drives.

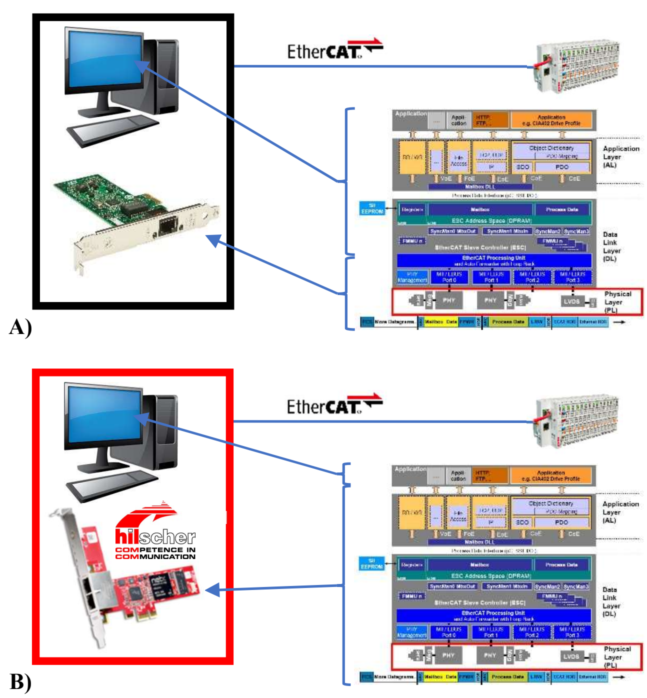

Figure 5. *Implementation of EtherCAT communication interface: A) 1st concept, B) 2nd concept*

To choose the best implementation of the communication interface, the authors decided to develop and implement two concepts for the implementation of this stack. In the first concept (Figure 5A), it was decided that the communication module in the data link layer and the physical layer of the OSI model would be based on the standard Intel 82574 Ethernet card. The application layer in this concept will be entirely based on the EtherCAT stack software module - the EtherLab open programming library [7]. This library enables the implantation of the driver module of the used network card in two variants. The first variant uses the dedicated *e1000e* driver for the 82574 Ethernet card. The second variant uses a *generic* general-purpose driver. The authors used both variants of drivers in this concept.

The second concept (Figure 5B) assumes using a dedicated EtherCAT communication card. In this case, the authors decided to use the Hilscher cifx-50RE card. The communication card has the EtherCAT (hardware stack) stack wholly implemented in this solution. To integrate the card stack with LinuxCNC software, the authors developed a dedicated software interface for communication with the EtherCAT Stack application layer on the card. Dedicated commercial libraries of the manufacturer were used.

4. RESEARCH

The accuracy of the positioning of the mechanical system in this type of machine is influenced by the mechanical structure of the machine itself and the CNC machine control system. The accuracy of the H-Bot machine operation largely depends on the synchronous operation of the servo drives. The authors decided to investigate the quality of machine operation communication, first focusing on the control system. The critical thing is the transfer and cyclicality data exchange between the controller (PC) and the peripherals - especially PMSM servo drives.

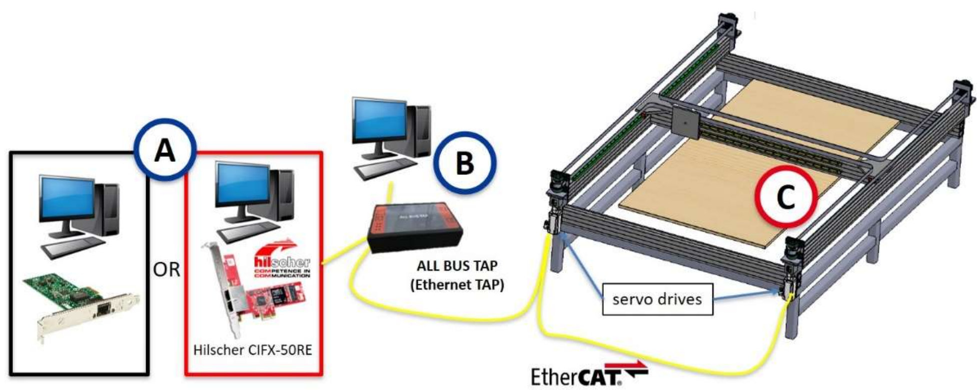

Figure 6.*Diagram of the stand for examining the jitter of EtherCAT cyclic communication: A) CNC controller with two different communication interfaces, B) measuring computer with ALL BUS TAP, C) H-Bot machine with servo drives*

The authors conducted control quality tests, particularly the developed EtherCAT communication interfaces in the CNC controller. The research measured the jitter of the communication cycle in the EtherCAT bus (connection of the CNC controller - servo drives) for all developed communication interfaces according to the aforementioned concepts 1 and 2. For this purpose, the authors connected the measuring device ALL BUS TAP to the EtherCAT bus, which is an Ethernet TAP device (Figure 6). The measuring device does not affect the quality parameters of EtherCAT communication (it is "transparent" for communication data). The device allows the measurement of time stamps, the arrival of data intended for drives, and data intended for the CNC controller system. The timestamp measurement data is sent to a second measurement computer that aggregates it. From these data, it is possible to calculate the time differences between individual time stamps, which determine the jitter of the communication cycle in the EtherCAT bus.

The tests were carried out for three different configurations of the communication interface. The first configuration is according to concept 1 with the *generic* driver variant, the second is according to concept 1 with the *e1000e* driver variant, and the third uses the cifx-50RE card (concept 2).

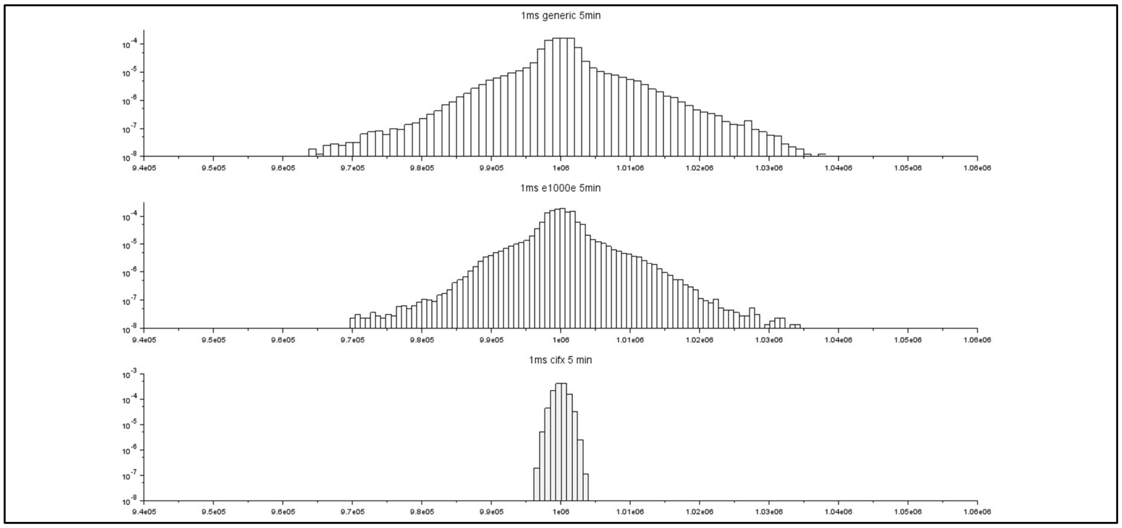

Figure 7. *Jitter- 1 millisecond EtherCAT cycle time*

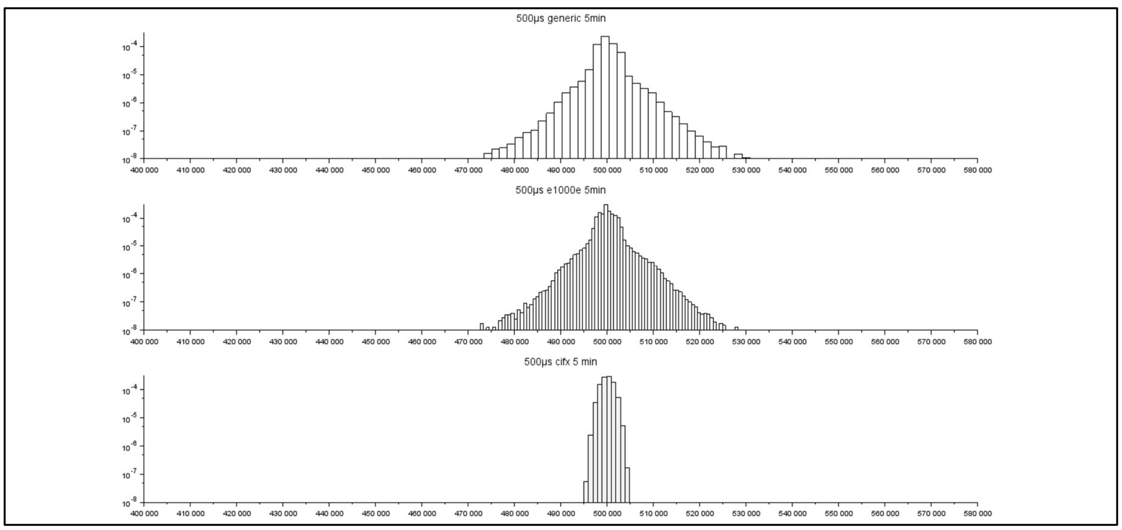

Figure 8. *Jitter - 500 microseconds EtherCAT cycle time*

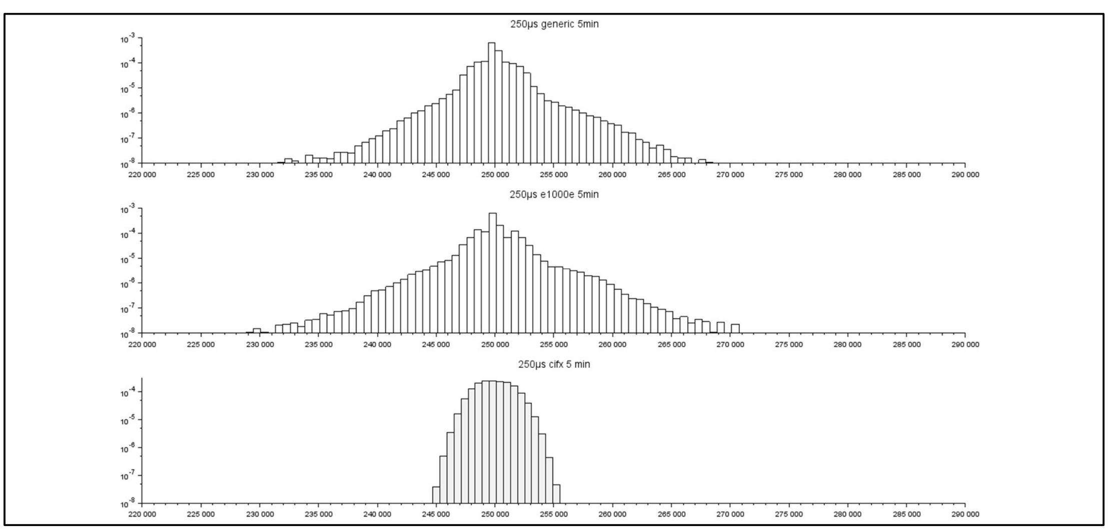

Figure 9. *Jitter - 250 microseconds EtherCAT cycle time*

Table 1. 1ms (300 000 samples) – jitter values			
	generic driver	*e1000e* driver	cifX-50RE card
Minimum	941350ns	964470ns	996130ns
Maximum	1047670ns	1038160ns	1003930ns
Range	106320ns	73690ns	7800ns
Standard Deviation	4011.3650ns	3424.3098ns	845.78597ns
Mean	999991.15ns	999990.96ns	999966.54ns

Table 2. 500µs (600 000 samples) – jitter values			
	generic driver	*e1000e* driver	cifX-50RE card
Minimum	400560ns	468480ns	494940ns
Maximum	569750ns	535590ns	504820ns
Range	169190ns	67110ns	9880ns
Standard Deviation	2519.5714ns	2542.4667ns	1186.0991ns
Mean	499995.46ns	499995.44ns	499982.97ns

Table 3. 250µs (1 200 000 samples) – jitter values			
	generic driver	*e1000e* driver	cifX-50RE card
Minimum	222560ns	220070ns	244110ns
Maximum	282240ns	282640ns	256110ns
Range	59680ns	62570ns	12000ns
Standard Deviation	1449.8119ns	1798.8300ns	1403.5689ns
Mean	249997.73ns	249997.72ns	249991.47ns

Tests were carried out for three different configurations of the EtherCAT communication interface in the CNC controller for three communication cycles with 1ms, 500µs, and 250µs. Communication cycle jitter data are summarized in Figures 7-9 and Tables 1-3.

In the case of a communication cycle of 1 ms, the jitter for the third configuration (using the cifX-50RE card) is the smallest of the other configurations (software EtherCAT stack implemented in the structures of the CNC controller). The situation is similar for shorter communication cycles - 500µs and 250µs. This result is in line with expectations because the dedicated and independent EtherCAT stack (implemented in the cifX-50RE card hardware) is not susceptible to interference in data processing compared to software solutions in the CNC controller (based on the Etherlab library).

However, the suspects about differences in the EtherCAT communication interface in the case of the first configuration using *generic* and *e1000e* drivers did not prove correct. It is expected that for the *e1000e* driver, the jitter spread values for all communication times will be significantly lower than for the *generic* driver. However, research shows that this difference is practically negligible.

5. CONCLUSION

The article describes the construction and operation of a CNC machine laboratory stand with H-Bot parallel kinematics using the EtherCAT bus. The basics of parallel kinematics for the H-Bot structure are presented. The developed numerical control system for machines was introduced and discussed. The research shows the results of the jitter of communication cycles (1ms, 500µs, and 250µs) for three different, developed by the authors, EtherCAT communication interfaces of the CNC controller. It can be concluded from the research results that the EtherCAT bus is most suitable for use in controlling CNC machines.

This is of particular importance in the case of further research on that stand, especially in developing and implementing advanced control algorithms and predictive maintenance in CNC machine control systems. The EtherCAT bus allows to connect of various types of control modules and measurement modules. In the future, it is planned to equip the H-Bot machine with sensors such as strain gauges (for measuring the tension of toothed belts) and accelerometers (single and triaxial - placed on a moving beam in the Y axis) connected to measuring modules with an EtherCAT interface. This will enable the aforementioned predictive maintenance research to be carried out in the future.

6. LITERATURE

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Laboratorijska CNC mašina sa H-Bot paralelnom kinematikom koja koristu EtherCAT magistralu

Rezime: *Ovaj rad predstavlja sistem upravljanja kinematikom H-Bot mašine. Tačnost mašine H-Bot zavisi od sinhronog rada servo pogona i mehaničkog dizajna. Dakle, na kvalitet kretanja mehaničkih osa utiču komunikaciona magistrala i sposobnost detekcije zazora i elastičnosti u osama mašine. EtherCAT – industrijska magistrala će se koristiti za komunikaciju između kontrolera i drugih elemenata sistema upravljanja mašinom. Svaka mehanička osa na H-Bot mašini je opremljena mernim sistemom pozicije . Laboratorijski štand je bio opremljen akcelerometrima. Planirano je izvođenje istraživanja u oblasti prediktivno održavanje i optimizacija putanje.*

Ključne reči: *H-Bot mašina, sistem upravljanja mašinom, EtherCAT, LinuxCNC*