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MECHATRONIC ENGINEERING – SCIENTIFIC SUPPORT FOR THE EFFICIENCY AND COMPETITIVITY OF INTELLIGENT INDUSTRY (4.0)

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Abstract: *The scientific paper deals with the role and support of Mechatronic Engineering and the competitivity of Intelligent Industry (4.0), presenting the generative developments of the new field and highlighting scientific and technological advances and innovative concepts. The scientific work also responds to the paradigm challenge of the European strategy to create and develop new scientific concepts and new intelligent multi-applied systems in new industrial and engineering value chains for the efficiency of products eco-innovation. Moreover, mechatronic engineering and respectively complex mechatronic products and systems are used in smart networks, with embedded sensors, with processing and actuation, made to take data and interact, the physical world with the virtual world, supporting in real time, performance assurance and applications in industry, economy and society.*

Also, the scientific paper concretely presents the adaptability of the new complex mechatronic concept, the realization of ultra-precise complex mechatronic systems of intelligent 3D control, in the industrial and laboratory metrological process, the realization of ultra-precise complex mechatronic systems of multi-application 3D remote control and remote monitoring in industrial and laboratory processes, the realization of Data and IT&C systems, necessary for the integration of the physical system with the virtual system, etc.

The 3D mechatronic systems, realize the functions of 3D remote control and remote monitoring within intelligent industrial processes.

Keywords: *Mechatronic engineering, competitivity of intelligent industry (4.0), European strategy paradigm, new scientific concepts, intelligent systems, new industrial value chains*

1. Introduction

The paper addresses the “challenge of the European strategy paradigm to create and develop new scientific concepts and new intelligent systems replicated in new industrial value chains,” which requires focusing, combining, and fusing various competencies and innovative solutions — especially new mechatronic technologies — and integrating them into advanced high-tech IT&C solutions and competencies for the efficiency and eco-innovation of products and systems, significantly more advanced and intelligent [6,7].

Moreover, complex mechatronic systems, are highly intelligent systems used in smart networks with embedded sensors, processing, and actuation elements. These are designed and built to collect data and interact — the physical world with the virtual world — aiming to support, in real time, guaranteed performance and safety in both standard and critical applications in industry, economy, and society.

In these mechatronic systems, they integrate and generate the overall behavior of mechatronic elements, including computing, control/remote control, detection/remote detection, and smart network components. These can be deeply integrated and assembled, and their actions can be secure and interoperable [1].

Therefore, it is emphasized that complex mechatronic systems are multi-applicative, adaptive, and future-ready, acting as driving factors for the sustainable development of many industrial, economic, and societal sectors (such as aerospace, energy and environment, construction, transportation, defense, healthcare, agriculture, etc.) [2,3].

2. Adaptability of the New Complex Mechatronic Concept

The adaptability of the new complex concept involves the flexible adaptation of intelligent system architectures, expressed through complex structures of specialized sensors and actuators placed on static and/or mobile physical work systems and equipment. These transmit information to smart 4G devices that process, store, and forward data to monitoring / remote monitoring entities or centers for command and/or database integration.

Thus, mechatronic systems will be designed, structured, and architected into specialized intelligent modules assembled into dedicated configurations that serve multiple applications and add value to all components/devices within the general system.

By using smart 4G devices, real-time remote monitoring, diagnostics, and interventions are enabled for all static and mobile systems and equipment.

These multi-applicative and adaptive mechatronic systems will take the form of “black box” entities, innovatively integrating hardware circuits and software for data capture, modeling, and communication to/from the “command center.”

The architecture of adaptive multiplicative mechatronic devices/systems will be modular, allowing the integration of additional smart “add-on” other devices dedicated to specific or specialized activities.

The types of data captured by these smart devices will be processed, normalized, and standardized by the parent mechatronic adaptive multiplicative system/device into formats that ensure interoperability with the real-time monitoring platform.

Between mechatronic adaptive multiplicative systems/devices and the command center, communication will occur via a secure information exchange protocol. This will record and display real-time data. The command center, operated via a WEB platform, will be able to issue real-time alerts and ON/OFF commands that will be sequentially transmitted to the parent systems/devices and then to the targeted smart devices.

This complex mechatronic concept can be applied in many industrial environments, such as:

- Real-time remote monitoring and control of the quality and operation of automotive electronic and control systems
- Real-time remote monitoring and control of parameters in complex thermochemical treatment installations under controlled atmosphere
- Real-time remote monitoring and control of hydraulic oil quality in agricultural machinery actuation systems
- Real-time monitoring and control of CO_2 and other exhaust emissions in the automotive industry
- Real-time remote monitoring and control of electronic and control systems for vehicle stability
- etc.

3. Overview of Ultra-Precise Complex Mechatronic Systems for Intelligent 3D Control in Industrial and Laboratory Metrology

Through the new complex concept of Integrative Intelligent Mechatronics, the architectural concept was created for new solutions involving ultra-precise complex mechatronic systems for intelligent and integrated control in the automotive industry, specifically for cast and machined automotive parts.

Integrative Intelligent Mechatronics technology is considered an advanced technology with rapid, efficient, and competitive effects, offering top-tier performance in the improvement, modernization, and development of products, processes, product systems and intelligent systems. It creates new solutions for industry, new connections, new interfaces, and total integrations, similar to human anatomy and functions, aligned with the needs of modern society.

In the architecture of integrative intelligent mechatronic technology, a substantial role is played by the software of the intelligent sensors integrated into the system. This includes informational modules for preprocessing, signal conditioning, feature extraction, defect detection, recalibration, and reconfiguration, such as:

- Initial preprocessing phase: Converts the signal into an engineering unit
- Calibration process: May include signal linearization using a simple lookup table approach with coefficients stored in the sensor’s electronic datasheet
- Alternative linearization technique: Involves summing the reciprocal characteristic of the sensor with the signal
- Additional calibration functions: Include eliminating polarization effects of the sensors
- Calibrated signals: Pass through a signal conditioning software module to extract a series of features that characterize the data
- Feature extraction: Derives hidden information from the sensor’s “signal history,” useful both as output data and as part of defect detection strategies
- Main derived features: Serve as components for self-diagnosis and defect detection
- Sensor management communication: Uses error code sets based on electronic mechanisms

Figure 1 illustrates the block diagram of the intelligent mechatronic system for integrated measurement and control, highlighting the main functional modules and their interconnections.

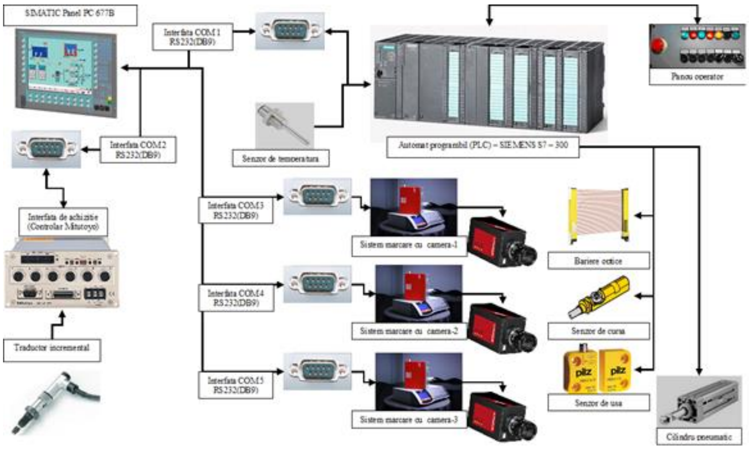

Fig. 1. Block diagram of the intelligent mechatronic system for integrated measurement and control

Legend:

1 – PC with visualization application;
2 – Optical safety barrier;
3 – Measurement station 1;
4 – Measurement station 2;
5 – Measurement station 3;
6 – Signal tower;
7 – Programmable logic controller (PLC);
8 – Sensor interface;
9 – Control panel

Fig. 2 Intelligent complex mechatronic system for measurement and control of automotive parts

4. Presentation Of Ultra-Precise Mechatronic Systems for Intelligent 3D Remote Control and Monitoring

The new complex mechatronic concept has been implemented in the construction of mechatronic systems for intelligent 3D remote control, aiming to fulfill several functions specific to the new concept, such as ultra-precise 3D remote control adapted to the appropriate environment (laboratory/industrial metrology), remote data transmission and transfer and remote monitoring of the intelligent control process via a command center (for ultra-precise 3D control), with information transfer via Internet and Intranet [4,5].

Below is the concept of a multi-application ultra-precise mechatronic system for intelligent 3D remote control and monitoring in laboratory or industrial metrology (Figure 3).

The ultra-precise mechatronic system is designed to perform displacement control functions along X, Y, Z axes and measurement (control) functions based on the system and data from the “ultra-precise 3D probe” integrated into the system.

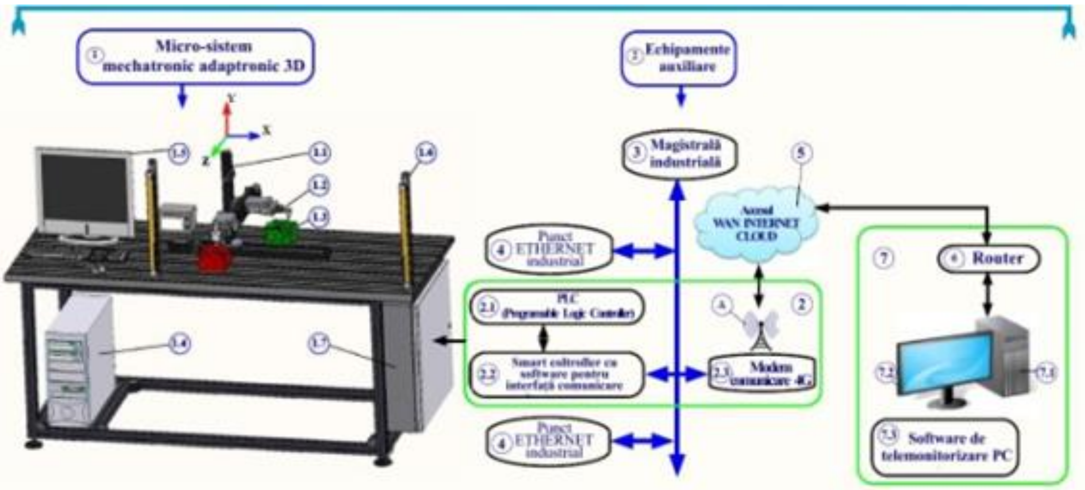

Fig. 3. Ultra-Precise Mechatronic System for Multi-Application Intelligent 3D Remote Control and Monitoring

1. 3D Mechatronic System:
1.1 Ultra-precise 3D measurement/control robot (x=300mm; y=200mm; z=250mm; accuracy: 0.1–1nm);
1.2 Ultra-precise 3D probe (fidelity 0.1 nm);
1.3 Part to be measured/controlled;
1.4 Local PC unit;
1.5 Visualization monitor and local user interface;
1.6 Laser safety barrier
1.7 Unit with control, actuation, and telecom systems;

2. Auxiliary Equipment:
2.1 PLC (Programmable Logic Controller);
2.2 Smart controller with communication interface software;
2.3 4G communication modem;
3. Industrial bus;
4. Industrial ETHERNET point;
5. WAN INTERNET CLOUD access;
6. Router
7. Control center
7.2 Monitor PC
7.3 Remote monitoring software

In 3D displacement mode, the mechatronic system can be operated both locally using pre-installed software on a PC with display and control interface, and remotely through position modeling and emulation. In 3D control mode, “position–probing information packets” are formed into “vector packets” for complex mathematical processing, either locally or remotely.

Switching between the two operating modes can occur at any time, and measurement points (3D control) can be stored for automatic operation in the PLC’s memory.

All these complex functions are achieved by functionally testing and integrating multiple intelligent subsystems.

The general block diagram of the ultra-precise mechatronic system also presents the mechatronic & cybernetic component structure for functional illustration:

- **On the local PC unit (1.4)**, data from the 3D mechatronic system is collected and transmitted to the SMART TELECONTROL system. The data provided by SMART TELECONTROL is packaged, compressed, and protected via a VPN system with a private key. After establishing bidirectional communication with the telemonitoring system, the data is sent and validated. Once unpacked, the collected information is inserted into a database where the components of the mechatronic microsystem are analyzed.

Additionally, the positions of the telemetry system are stored in the same database and replicated on the telemonitoring screen using software. Based on the received data, the software generates a high-fidelity 3D image. Where data is insufficient, interpolation from previous data is used to ensure smooth rendering. Upon request, the session and generated image can be saved for future use and analysis. The mechatronic microsystem can be controlled in real time using the TELECONTROL software.

- **Connections and interconnections** between subsystem modules and system architecture components vary depending on their type. The 3D mechatronic system and ultra-precise 3D probe (nanometric precision) may be equipped with intelligent data transmission interfaces such as serial, parallel, CAN, PROFIBUS, SSI, INTERBUS, ETHERNET, DEVICENET, and other specialized types.
- **The 3D mechatronic system (1)**
- **The Programmable Logic Controller (PLC) (2.1)** is a digital computer used for automating cyber-mixmechatronic processes. It stores the specific control program for the 3D microsystem (X, Y, Z axes or control robot) and synchronously receives data from the 3D probe.

This controller is designed for multiple inputs and outputs, operates across extended temperature ranges, and withstands vibrations from machine kinematics and accidental impacts. The control program is typically protected by a backup or stored in non-volatile memory. The PLC operates in “real time,” meaning outputs must respond to inputs within a limited time frame to avoid unintended operations and undesirable outcomes.

- **The intelligent telecontrol module (2.2)** can be implemented using either a RISC architecture microcontroller or FPGA and connects the PLC to the 4G telecom modem via RS232 protocol.
- **Various public or private networks are used for 4G access (2.3)**. A range of compatible modems support RS232 data protocols. Event-driven or cyclic data processing is performed using specialized telecontrol protocols, allowing operators to manage the process efficiently. One or more advanced software platforms are used for remote connection via modern GPRS technologies or the global WAN Internet network, commonly used in other mechatronic automation equipment.
- **At the Telecontrol Center (7)**, Internet access is provided via a router with VPN functionality for initial data security. A second security layer may be implemented using a proprietary encryption algorithm and specific firewall configuration on the PC operating system (Windows or Linux). Programming a network application requires a Real-Time Operating System (RTOS), which supports multitasking, resource allocation, and memory constraints for Blackfin process programming.
- **The software application (7.3)** is a web-based telecontrolling desktop tool with two components: a PHP web service and a telecontrol front-end software with real-time emulation capability. The PHP service integrates the telemetry database backend and returns results to the front-end in a specific telecontrol format. To minimize real-time data transfer, only measurement-mode data is requested. Upon receiving data, the front-end software generates a real-time emulated virtual model of the 3D cyber-mixmechatronic system.
- The structural component of testing, evaluation, and validation aims to configure the final system to meet initial requirements and specifications.

To achieve this, the following aspects are detailed:

- ➢ Determining criteria for testing, evaluation, and validation of the 3D mechatronic system
- ➢ Describing categories of tests and evaluations involved
- ➢ Planning testing and evaluation during system development

- Preparing the mechatronic system for testing and evaluation.

5. Presentation Of Data And IT&C Systems Required For Integrating The Physical And Virtual Systems In A 3D mechatronic Intelligent System For Industrial And Laboratory Metrology

5.1. Intelligent Architectures Of The Physical And Virtual Systems (Figures 4 And 5)

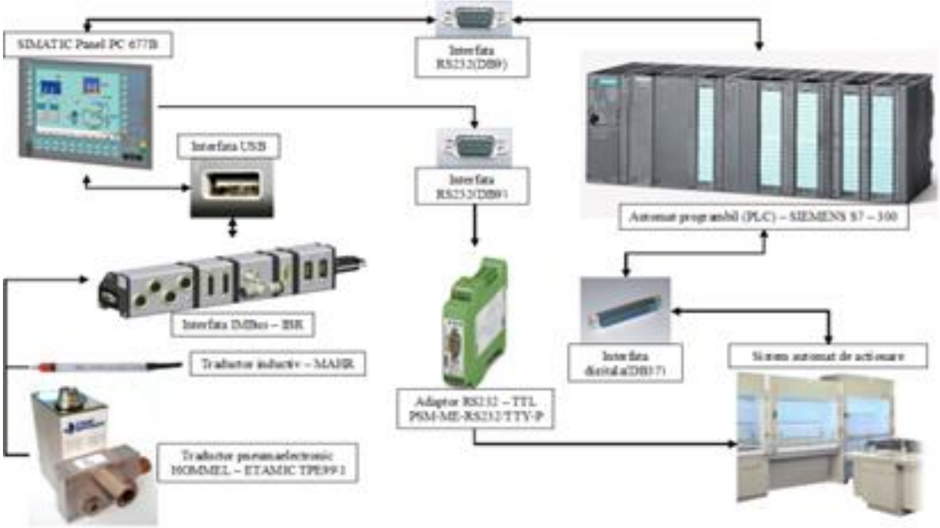

Fig. 4. Intelligent Architecture of the Physical System

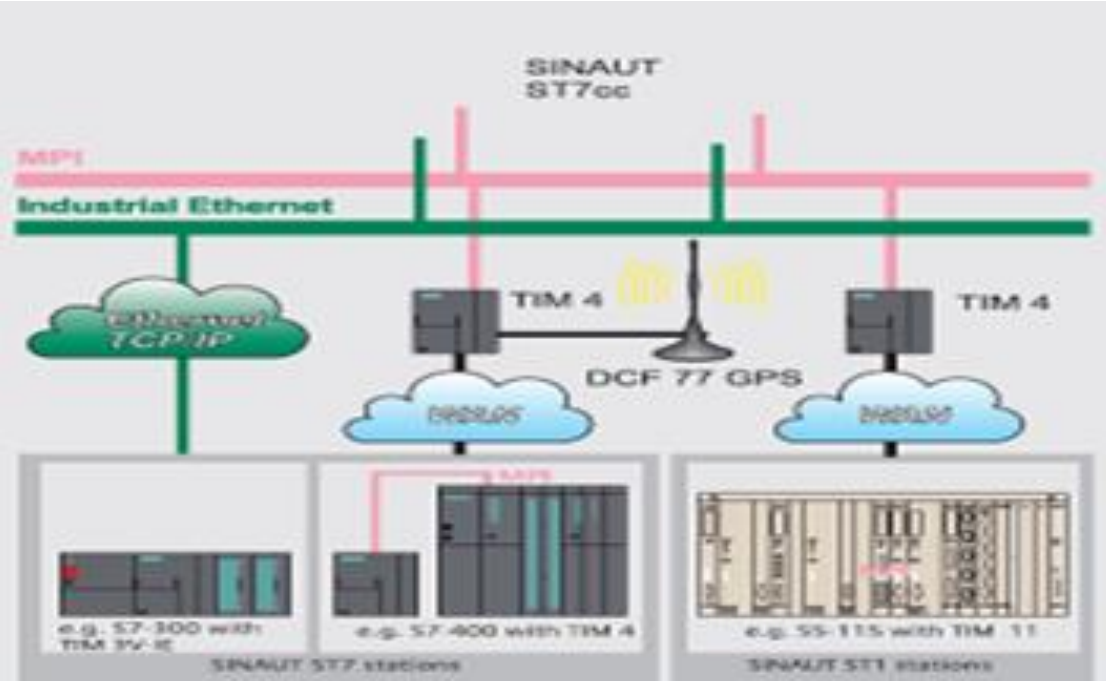

Fig. 5. Intelligent Architecture of the Virtual System

Within these figures, an industrial computer, a programmable logic controller, a signal adapter, an interface for acquiring electrical signals, a marking system equipped with a camera, and pneumatic-electronic and inductive transducers were employed. In the figure, the automatic actuation system transmits to the programmable logic controller, in digital format, the moment when the measurement should be performed as well as its current state (errors, measurement status, operating status). Once

the programmable logic controller receives the measurement command, it forwards it to the industrial computer, which—through the acquisition interface—carries out the measurements, processes them, displays the results, and transmits them back to the automatic actuation system via a communication adapter.
- The PC computer has the function of measuring, with the aid of transducers, 18 dimensions and verifying whether the measured values fall within predefined ranges. The visualization of the measured data is achieved by displaying the value of each measured dimension and by coloring these values in green or red;
- The use of the programmable logic controller was required by the communication of the automatic actuation system, through which the communication between the industrial computer and the controller was carried out;
- By using the adapter, the results concerning the inspected part are transmitted to the automatic control system;
- In the figure, the measurement system acquires data from the transducers through the acquisition interface—in this case, a Mitutoyo controller—and the data are processed and stored by the industrial computer;
- Depending on the measurement results, the part is marked using a marking system equipped with a camera for verifying the execution of the operation;
- This dimensional control system is equipped with a programmable logic controller that manages the temperature sensors, optical barriers, travel sensors for the actuation system, the actuation system itself, and door presence sensors, while also enabling interaction between the user and the dimensional control system through the operator panel;
- The optical barriers and door sensors are used to ensure user protection in accordance with the standards imposed by the client;

5.2. Data Acquisition

In this case, it is considered that the control equipment is located at a distance from the controlled process. The actuating elements receive command signals through the communication network, while the data acquired from the process by the transducers are directed to the controller also via the network. Due to this topology, additional delays occur as a result of data transfer. These network delays can be classified according to the direction of data transfer as sensor–controller delays and controller–process delays, both being present on the forward path as well as on the feedback path. For ease of analysis, the delay times can be grouped into a single time constant, referred to as the 'control delay.' Both types of network-induced delays may be either shorter or longer than the sampling period T.

In the first case, the process can be conducted under optimal conditions (assuming that no packets are lost).

In the second case, major discontinuities in the control process occur, which may lead to unsatisfactory developments and to the loss of process stability.

Based on the experiments carried out, the following stages are proposed:
- Evaluation of the dynamic characteristics of the controlled process, including the actuating elements and the transducers (the fixed part of the control elements)
- Selection of the sampling period in compliance with stability and performance requirements
- Testing of the network to be used in the control and/or monitoring process, taking into account the average delay times and the probability of error (packet loss).

If these delay times are much smaller than the required sampling period, the process can be controlled by incorporating a delay block into the fixed part of the regulation elements. If the delay times become comparable to the sampling period, it is recommended to use a structure that employs a Smith predictor;

The delays consist of at least the following parts:

●● Waiting time – this is a delay in which a source (the controller) must wait for the availability of the network before sending the data packets;

●● Sampling time – this is a delay caused by the insertion of the data packet into the network;

●● Propagation time – this is a delay caused by the transmission of the data packet through the physical network. The propagation time depends on the signal transmission speed and the distance between the source and the destination;

●● These three types are fundamental delays that occur in a local network. When data packets are transmitted over the network, additional delays may arise, such as the waiting time at a switch or router, and the propagation time between network nodes. Delays also depend on other factors, such as the maximum bandwidth length and the size of the data packets;

●● Based on the experiments conducted, three distinct cases of remote process control have been identified:

●●● Case 1: Predictive control for time-delay systems.

●●● Case 2: Adaptive predictive control using a delay calculated a posteriori: based on the experimental values of the delays, an average value was computed, which is then used in the control algorithm.

●●● Case 3: Adaptive predictive control using a variable delay estimated a priori: based on the experimental values of the delays, the delay time was estimated for the next sampling period.

5.3. Telemonitoring And Teleservice Software On A Pc Platform (Fig. 6)

The software application is written in Visual C++. The PC running the application uses a modem configured as a client. This modem connects to the PC RS232 serial interface. The modem configured as a server connects to the mechatronic equipment being monitored, also using an RS232 connection.

The initial screen of the software application is shown in Figure 6. Indicator 1 represents the state of the digital inputs Ixx at the bit level. Indicator 3 represents the current values of the digital outputs Qxx. Validation controls 2 (checkboxes) provide a convenient means for the user to set or reset the desired value for output Qxx. Button 4 is pressed to establish the connection between the application and the monitored equipment. Field 8 represents the list of commands that can be sent to the monitored equipment. Field 7 is optional. The start address 6 is filled in with a numeric value in the range 0–7, specifying the address of the first selected I/O module. Edit control 5 is filled in with the number of numeric values to be issued or for which the actual value retrieved from the monitored cyber-mechatronic equipment is requested.

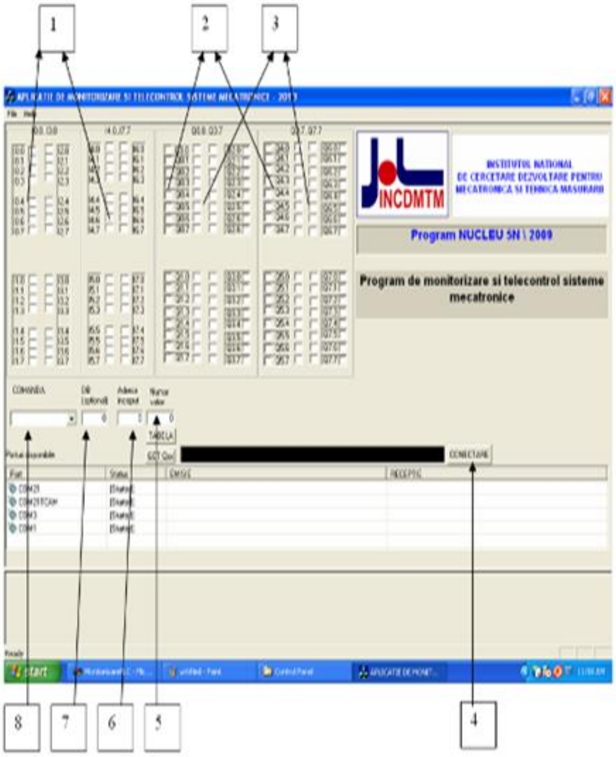

Fig. 6. Telemonitoring and Teleservice Software on a PC Platform

For reading the digital outputs, the user selects the command 'bord' from list 8 and enters the start address in editor 6 as well as the number of bytes in editor 5. The message is then sent to the monitored equipment (Figure 7). The response received is displayed through indicators of type 1.

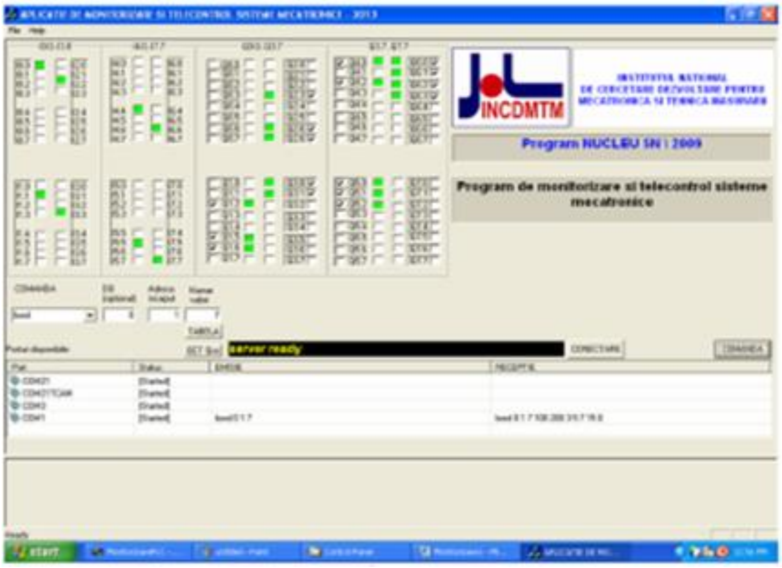

Fig. 7. Displaying the Message to the Monitored Equipment

For writing the digital outputs, the user selects the command 'bowr' from list 8 and enters the start address in editor 6 as well as the number of bytes in editor 5. Then, button 9 (table) is pressed. An editable table 11 appears. The number of columns is equal to the number of output bytes whose values will be transmitted to the monitored equipment. In each column of the table, the operator can enter numerical values between 0 and 255.

The assembled numerical values of each output byte are placed in the corresponding field. The command message is sent to the monitored system (Figure 8). The response received is displayed through indicators of type 1.

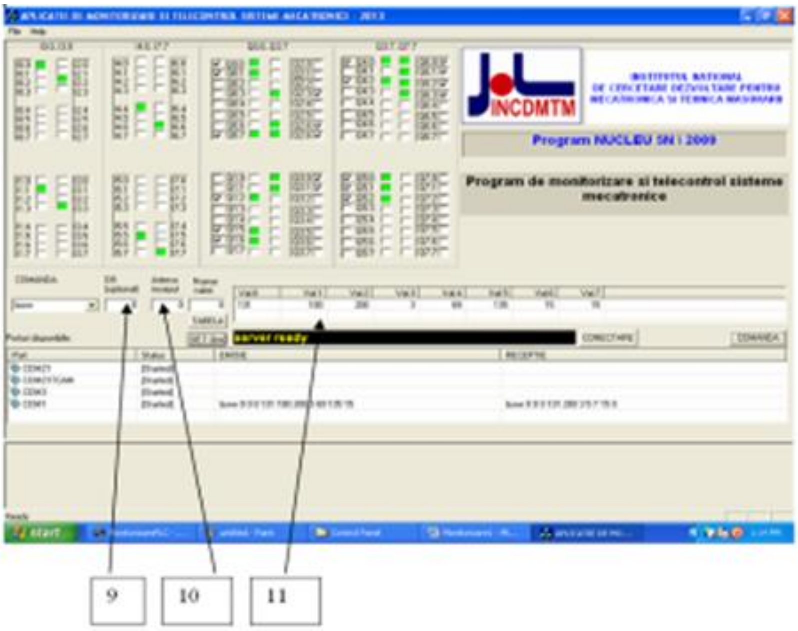

Fig. 8. Sending the Message to the Monitored Equipment

6. Conclusions

The purpose of this scientific work is to present the new mechatronic ultraprecise concept for intelligent 3D multi-application remote control and remote monitoring,' used in the construction of mechatronic ultraprecise systems for intelligent 3D remote control intended for laboratory metrological processes and/or industrial processes in the automotive, aerospace, hydronic and pneutronic, medical and biomedical industries, etc.

The 3D mechatronic system is designed to perform 3D telecontrol and telemonitoring functions within intelligent metrological and/or industrial processes, through ultraprecise X, Y, Z displacement signals and information, as well as the measuring/control probe in 3D, based on the preinstalled PC program and the command software for modeling and remote positioning. In this way, the 'position–probing information packets' are structured into 'vector packets' for complex mathematical processing, which can be carried out both locally and remotely.

The 3D mechatronic system is based on intelligent architectures of specialized sensors and actuators, as well as specialized static and mobile work modules, which transmit information to intelligent 4G mechatronic units. These units process, store, and transmit the data to monitoring–command entities or databases, through the cybernetic and integronic system – the physical (mechatronic) system fused with the virtual system (Internet, Intranet).

References

[1] Phatak, Sujit S., D.J. McCune, and George Saikalis. "Cyber Physical System: A Virtual CPU Based Mechatronic Simulation." *IFAC Proceedings Volumes* 43, no. 18 (2010): 405-410. https://doi.org/10.3182/20100913-3-US-2015.00077.

[2] Zhou, K., Ye Cen, J. Wan, B. Liu, and L. Liang. "Advanced Control Technologies in Cyber-physical System." Paper presented at the 5th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC 2013), Hangzhou, China, August 26-27, 2013. doi: 10.1109/IHMSC.2013.284.

[3] Gheorghe, Gh. *Intelligent Systems Adaptronics / Adaptronica Sistemelor Inteligente*. Bucharest, AGIR Publishing House, 2014. ISBN: 978-973-720-509-4.

[4] Gheorghe, Gh. *Mechatronics & Cyber–Mechatronics Systems / Mecatronica & Sistemele Cyber – Mecatronice*. Bucharest, CEFIN Publishing House, 2015. ISBN 978-606-8261-22-5.

[5] Voicu, Adrian, Gheorghe I. Gheorghe, and Liliana Laura Bădița. "Studies and research on the measurement and 3D integrated control of complex components from automotive industry by laser scanning." Paper presented at the 12th International Conference of Numerical Analysis and Applied Mathematics ICNAAM 2014, Rodhos, Greece, September 22-28, 2014.

[6] Lincaru, Cristina, Florentina Badea, Speranta Pirciog, Adriana Grigorescu, Sorin Ionut Badea, and Cristian Radu Badea. "An Overview About Mechanics Developments and Achievements in the Context of Industry 4.0." Paper presented at the International Conference on Reliable Systems Engineering (ICoRSE) – 2023, Bucharest, Romania, September 7-8, 2023. *Lecture Notes in Networks and Systems* 762 (2023): 17-41. DOI: 10.1007/978-3-031-40628-7_2.

[7] Badea, Florentina, Gabriela Tudose, Cristina Lincaru, Speranta Pirciog, Sorin Ionut Badea, and Cristian Radu Badea. "Neighbor-Joining Analysis of Mechanics and the Industry 4.0 Domains." Paper presented at the International Conference on Reliable Systems Engineering (ICoRSE) – 2023, Bucharest, Romania, September 7-8, 2023. *Lecture Notes in Networks and Systems* 762 (2023): 42 - 55. DOI: 10.1007/978-3-031-40628-7_3.