DIGITAL TRANSFORMATION OPPORTUNITIES REGARDING MACHINE TOOLS AND INVESTIGATION OF MILTEKSAN INDIGENOUS CNC CONTROLLER DEVELOPMENT EFFORTS

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ABSTRACT

In this study, first of all, the global position of the machinery manufacturing industry in Turkey is revealed and the important place held by numerically controlled benches (CNC) in the manufacturing industry is substantiated with figures. Components that create added value in CNC machines are analyzed item-by-item. It is observed that the control system comprising of electronic hardware and software create the most added value. Global trends suggest that with the advent of new generation CNC control systems this situation will further improve in favor of software. Efforts of MILTEKSAN initiative, that emerged as a co-operative role model to capitalize on digital transformation opportunities with the proliferation of new generation CNC controllers, on the development of indigenous CNC controller hardware and software are investigated and the critical role of sector clusters in this regard are emphasized.

Keywords: Turkish machinery manufacturing industry**,** CNC controller, digital transformation

1. INTRODUCTION

Machines use power to perform a task or action, reducing the amount of human work required to complete it. Machines can be mechanical systems, that include computers and sensors to control and monitor output. We need machines for transportation, for manufacturing gas turbine blades of a turbojet engine, for manufacturing dental implants and for just about anything. There are machines that in effect produce other machines. They are often referred to as “mother machines”. Machinery manufacturing industry produces these mother machines and therefore is a key industrial sector that can trigger sustained growth of an economy.

Through all four industrial revolutions machinery manufacturing has played a pivotal role. Digitalization is changing the way machines are designed and built. With the help of machines humanity has triumphed over the forces of nature after a long journey. Engineers managed to used laws of physics to improve human condition. A great thinker as his name implies and a pioneer was Archimedes. Due to Archimedes’ discovery of the principle of mechanical advantage in the lever in the third century, simple equipment such as levers, pulleys and screws operated on this very principle. The first industrial revolution came when the way these machinery was powered has shifted from animals, people, natural forces to steam power. This was a long overdue shift since the first invention of external combustion machine, the so called “aelolipile”, was by another Greek scientist, Hero of Alexandria [Hero, 1851] around 1st century B.C. With the last industrial revolution that we are experiencing today, almost two millennia after Archimedes and Hero, added value in manufacturing is shifting from mechanics to software. Global economy is becoming ever more software driven. In this paper we are going to substantiate this claim with our findings and industrial trends.

Note that the complex machinery manufacturing process relies on several manufacturing methods including forging, stamping, bending, forming and machining for individual metal parts. The parts are then joined together using several techniques such as welding and assembling. A machinery manufacturing facility uses a multitude of manufacturing and metal forming methods to make different components of the machine. Furthermore, complex parts may require significant precision and are impossible to manufacture by human-operators.

A significant portion of the industry falls into metalworking machinery manufacturing, which makes mother-machinery to form, shape and cut metal. Computer numerical controlled (CNC) machines have revolutionized the metal manufacturing industry in the 1980s and 1990s and the proliferation of CNC machines into the industry has completed. These include CNC mills, lathes, plasma cutters, electric discharge machines, multi-spindle machines, Swiss-type lathes, water jet cutters, punch presses etc.

Today however there exist new challenges that cannot be addressed by conventional CNC controllers that reached a saturation. Nowadays machinery manufacturers have an urgent need to design for digitalization. Because their customers are going through rapid change as we enter Industry 4.0 and are now demanding smart, data-driven equipment able to connect the internet to other manufacturing systems. Such machines can be connected from day one, so that breakdowns can be detected remotely and quickly in order to prevent machine downtime and to reduce repair costs. Manufacturers are also under pressure to build personalized, individual machines under surmounting time pressures. Small batch sizes of machines, often as small as one, must be built as efficiently and cost-effectively as possible. Energy costs are soaring and expected to stay high for a while at least. Energy efficiency and manufacturing time are also becoming dominating concerns. Conventional controllers fail short of addressing these concerns.

Conventional CNC controllers rely on dedicated specialized hardware. The rapid advance in computers has made PC-based automation a reality. Industrial PC’s (IPC) are expected to replace dedicated hardware. IPC based automation also offers significant flexibility for software developers. Value added in the controller is shifting from dedicated electronic hardware to software day-by-day enabled by IPC based automation. New generation data buses such as EtherCAT make it possible to carry significant loads of data in a real-time fashion. Advancements in real-time operating systems made them within the reach of any engineer with enough knowledge in the domain. These were once quite expensive proprietary pieces of software available in certain fields such as aircraft avionics. Today even Linux has several kernel options to support real-time behavior.

Based on the aforementioned arguments one can safely claim that we are experiencing the downing of a new generation CNC controller market. Timing is ripe for bringing innovative solutions. On the other hand, CNC controller market structure exhibits an oligopolistic competition scheme. Therefore, penetrating into the market with a novel new generation

CNC controller against the market forces is a challenging task and cannot be accomplished without support from local authorities and planning in a governmental scale. Sector clusters, government entities can play a significant role in this regard to support a sustainable industrial development since these controllers are at the heart of the manufacturing industry and are also of strategic importance. Four and higher axis controllers are subject to export controls, these regulations prevent and delay machine manufacturing industry. Although only 5% of these machines are used for military purposes and the remaining 95% is for the civilian market having the ability to produce an indigenous CNC controller will improve the capabilities of Turkey significantly. This paper provides a case study in the CNC controller development efforts of the MILTEKSAN initiative.

2. OVERLOOK INTO THE TURKISH MACHINERY MANUFACTURING INDUSTRY

Turkish machinery sector is a thriving industry. Figure 1 shows turnover of machinery and manufacturing industries. Figure 2 shows the share of machinery industry within the manufacturing sector. At the end of 2021, Turkey's machinery imports increased by 23% compared to 2020 and reached 31 billion USD. The total turnover of the Turkish machinery industry increased by 32.6% in 2020 and reached 158.6 billion TL. The Turkish machinery manufacturing industry added 40.6 billion TL to the country's economy in 2020, with a total of 17,680 companies and 248,000 direct employment as shown in Figure 3.

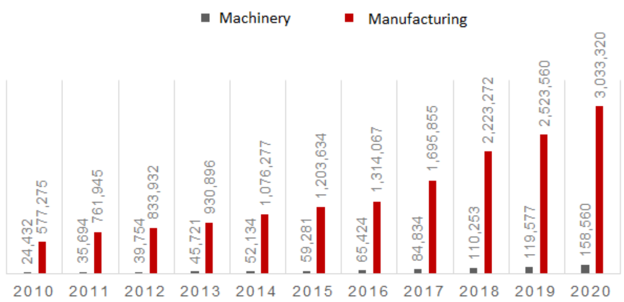

Figure 1. Turnover of Machinery and Manufacturing Industries, in million Turkish Liras (Source: TÜİK).

On the other hand Turkish machinery exports account for only a very small fraction of global machinery exports as outlined in Table 1. Furthermore, a company in the manufacturing sector on the average has a turnover of 1.2 million USD and 14.4 employees as shown in Figure 4. Figure 5 shows the number of ventures in the Turkish machinery and manufacturing industries. All these data suggest that Turkish machinery and manufacturing industries are lagging far behind their global competitors.

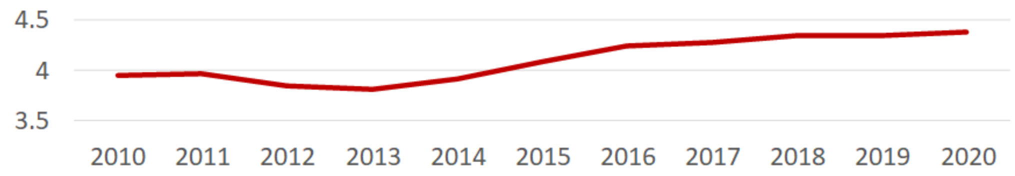

Figure 2. Share of Turkish Machinery Industry in the Overall Turnover of Manufacturing Industry (Source: TÜİK).

Among the long-term goals of the Turkish Machinery Industry, targets such as taking a 15% share in exports by 2030 and increasing the US dollar/kilogram value in exports to 15 shall only be achieved through technological transformation and innovation activities that require structural improvements. In a foreign market research commissioned by the Machinery and Accessories Exporters' Association (Makine ve Aksamları İhracatçıları Birliği), it is predicted that Turkey's machinery exports may reach 63 billion USD in 2030, if supported by government with appropriate measures.

Table 1. Global Machinery Exports and Share of Turkey, in million USD (Calculated from Trademap and TÜİK data).

Year	Exports of Turkey	Global Exports	Share of Turkey (%)
2016	9.226	1.192.161	0.77
2017	10.448	1.319.968	0.79
2018	12.350	1.451.430	0.85
2019	13.379	1.417.916	0.94
2020	12.526	1.298.915	0.96

Table 2 demonstrates high technology exports of Turkey and global competitors in 2017. According to the statistics of the Turkish Ministry of Commerce, Turkey's export rate based on high technology level is 3.5% in 2018. The low technology-based export rate was on the hand 32.6% in the very same year. Developing, producing and exporting high-tech products is of key importance for the sustainable development and development of any country.

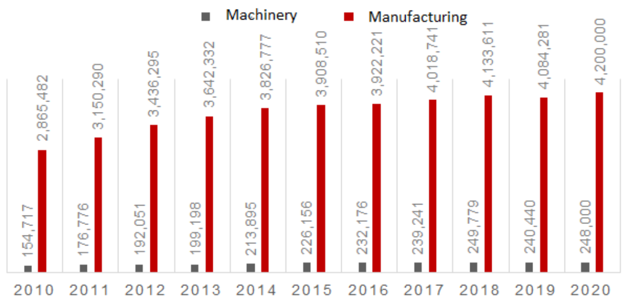

Figure 3. Employment of Machinery and Manufacturing Industries in Turkey (Source: TÜİK).

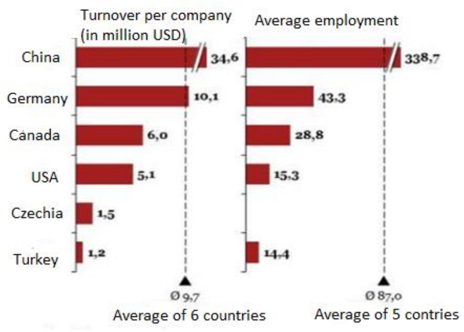

Figure 4. Turnover per Company and Average Employment in Manufacturing Industry in Turkey and Five Competitors (Source: Euromonitor, TÜİK. Czechia does not provide employment data).

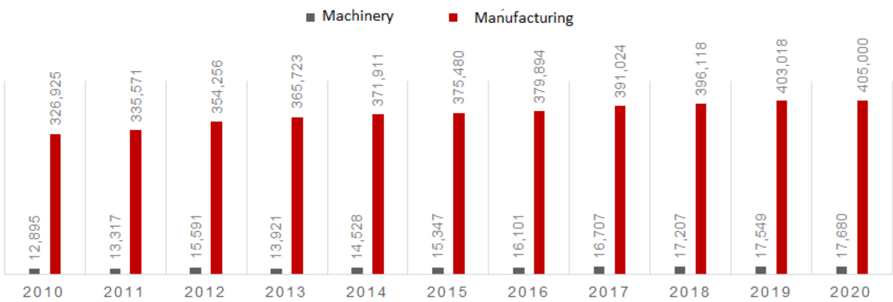

Figure 5. Number of Ventures in the Turkish Machinery and Manufacturing Industries (Source: TÜİK).

Table 2. High Technology Exports of Turkey and Global Competitors

(Source: Trademap & TÜİK).

Competitors	Total High Technology Exports (2017)	Total Machinery Exports (2017)	Percent Share of High Technology
China	35,788.7	457,864.3	7.82
Germany	3,841.3	245,364.2	1.57
USA	3,449.1	171.676,1	2.01
Czechia	1,322.2	33,872.2	3.90
Canada	222.6	28,760.9	0.77
Turkey	37.9	15,946.9	0.24

Figure 6 shows imports of machine tools’ electronic components. As seen from Figure 6 the trade imbalance is against Turkey and Turkey is heavily importing electronic items. This alone suggests that Turkey needs to develop its own indigenous solutions to tackle the trade deficit and foreign dependency in the machine tools sector.

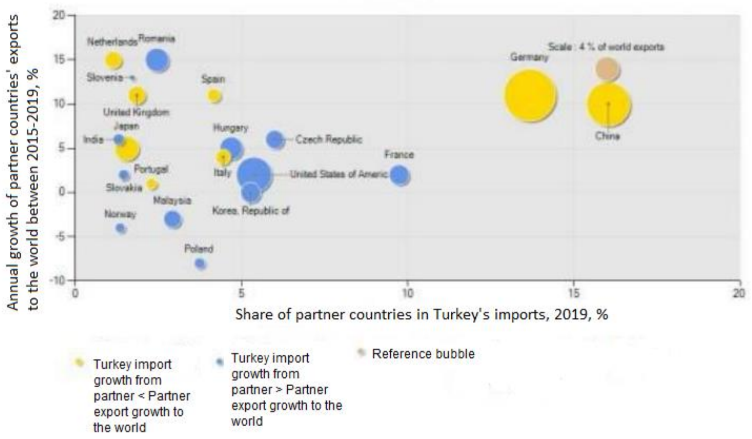

Figure 6. Imports of Electronic Components of Machine Tools (Source: trademap.org)

3. CNC MACHINES AND CONTROLLER MARKET

The First CNC Revolution

The first numerically controlled (NC) machines were built in the 1940s and 1950s, by modifying existing tools with motors that moved the tool or part to follow points fed into the system on punched tape. These primitive servo-mechanisms were then swiftly enhanced with analog and digital computers, creating the modern CNC machine tools that revolutionized the machining processes.

a. A Traditional CNC Controller

b. A New Generation CNC Controller

Figure 7. Two Generations of CNC Controllers.

The introduction of CNC improved machining quality, reduced machining times and made possible manufacturing of complex shaped parts that were otherwise not manufacturable by human operators.

A Paradigm Shift Effecting CNC Controllers

CNC controllers have completed their proliferation across the machining industry in the 1980's and 1990's. Thirty years later, the next step forward is a paradigm shift that is brought by Industry 4.0 revolution. Figure 7 shows a classical and a new generation CNC controllers. New generation controllers have less dedicated hardware and are more software driven. This is clearly apparent in the user interface design. New generation controllers operated much the same way as tablet computers. UI design can easily be changed and customized, these devices often support connectivity features that Industry 4.0 requires (i.e. networked operation, dark factories, ERP integration). Easily new applications can be developed and deployed on these controllers, much like loading a new application onto a tablet device or a cell phone. Software is the dominating factor in this paradigm shift and it is offering vast opportunities for CNC controller manufacturers and end-users. In the next two decades at most the existing old generation controllers will be totally replaced by these new generation controllers.

Structure of the CNC Controller Market

According to Markets and Markets (2021) the global CNC controller market size is valued at USD 2.8 billion in 2021 and is projected to reach USD 3.4 billion by 2026; it is expected to grow at a CAGR of 3.6% from 2021 to 2026.The growth of the CNC controller market is driven by rising adoption of industrial automation in manufacturing industries and increasing demand for mass production across a number of industries. The market on the other hand exhibits an oligopolistic competition structure wherein the majority of market share is divided across few international companies, namely: FANUC, Siemens, Mitsubishi Electric, DMG MORI, and Haas Automation. There are couple of dozen other manufacturers with insignificant market shares each. Although there exists an opportunity with the advent of Industry 4.0 in terms of new generation CNC controllers, entering in the market and competing against an oligopoly is difficult without proper planning and governmental support.

Where Does Value Added Come from in CNC Machines?

In this section we examine where the most added value is in the CNC machine manufacturing industry. Table 3 shows the cost breakdown structure of a typical 5-axis lathe manufactured in Turkey while also discriminating imported and domestic goods. Costs are presented in Euro rather than Turkish Lira as these prices are far more stable.

Table 3. Cost Breakdown Structure of a Typical 5 Axis Lathe Manufactured in Turkey in the Year 2022.

CHASSIS		
Domestic	Steel-Welding-Consumables	13.420,00 €
MECHANICS		
Import	Reductor X-Axis	
Import	Reductor Y-Axis	
Import	Reductor Z-Axis	
Import	Reductor A-Axis	
Import	Reductor C-Axis	
Import	Linear Rail	
Import	Rack & Pinion	
Import	Ball Screw	
Import	Bearings and fasteners	12.150,00 €
ELECTRICAL & ELECTRONIC		
Import	Spindle	
Import	5 Axis Controller Unit (Hardware)	
Import	15” Monitor	
Import	Control Panel	
Import	5-Axis Controller Software	
Import	Tool Center Compensation Module	
Import	Input Module 5-10 kW	
Import	Y1, Y2, X Motor 1.48 kW 3000 rpm Incremental Encoder	
Import	Z Motor 0.82 kW Braked Incremental Encoder	
Import	C Motor 0.82 kW Absolute Encoder	
Import	A Motor 0.5 kW Braked Absolute Encoder	
Import	Axis servo drives (X,Y1,Y2,Z,A,C)	
Import	Servo and encoder cables	
Import	I/O Module	
Import	Electrical Pane Accessories	
Import	Proximity Switches	
Import	Buttons and Limit Switches	39.400,00 €
ACCESSORIES		
Domestic	Electrical Pane	7.740,00 €
LABOR		
Domestic	Labor	5.200,00 €
	Import Total	**51.550,00 €**
	Domestic Total	**26.360,00 €**
	Overall Cost	**77.910,00 €**

Imported costs account for 66% of overall cost. Furthermore, electronic hardware and software algorithms are the most crucial parts of the system. For example, controller software beyond 3-axis is often subject to export control regulations and therefore the machine manufacturer has to present an end-user certificate. This picture clearly shows how limited the added value of the Turkish machine manufacturing industry is in its present form. Turkish machinery industry is literally doing nothing but the heavy-lifting. If value added per unit weight is considered, the dominance of electronics and software would become far more pronounced. Consequently, developing controller hardware and software seems the only way out to increase value added and to transform the overall structure of the machine tools industry in Turkey.

4. THE ROLE OF INDUSTRY CLUSTERS AND GOVERNMENT: A CASE STUDY OF MİLTEKSAN INITIATIVE

In this section the role of industry clusters and government are briefly discussed and a case study on how MİLTEKSAN initiative has formed is presented.

Industry Clusters and Government Harmonization

For a country to build and maintain a complex and diversified production structure it definitely needs to put emphasis in investment goods especially regarding four heavy industrial sectors (electricity, metallurgy, mechanical and electrical industries, chemicals). The concentration of capital should be allocated into investment goods rather than production goods. This in turn shall bring a potential of international competitiveness through the use of advanced technology [Milor, 1989].

The concentration of investments in the investment goods sectors characterized by the use of advanced technology, a potential for international competitiveness, and high degrees of corporate concentration should be in line with planning priorities [Milor, 1989]. Diversification of industrial structure and achieving self-sufficiency is of key importance. In the post-pandemic era where it is impossible to repair broken supply chains and increasing security concerns this statement is ever more true. Machinery sector is of strategic importance. CNC controller play a vital role in this industry.

Public policymakers need to by-pass certain vested interests in less productive sectors of industry [Milor, 1989]. In order to assist the public sector and co-ordinate efforts between the public and the private sector industry clusters can play a significantly positive role as long as they do not represent an interest group in an obsolete and less efficient industry. SAHA-Istanbul Defense and Aviation cluster already represents a high-tech industry and is the largest cluster organization in Europe within its domain. Although SAHA-Istanbul's primary concern is defense and aviation its Machinery Committee played a leading role in the establishment of MİLTEKSAN, a joint stock company whose primary undertaking is the development of a new generation five axis CNC controller. Figure 8 shows a moment from a SAHA-Istanbul Sub-Committee Meeting that eventually led to MİLTEKSAN's establishment by 11 distinct companies working in machinery manufacturing, control technologies, robotics, CAM software, digital transformation and servo-motors. MİLTEKSAN as a legal entity encapsulates all the foreground intellectual property in the process of CNC controller development. The list of MİLTEKSAN's founding partners was also coordinated between SAHA-Istanbul and Ministry of Science, Industry and Technology. This coordination was fruitful in best matching companies with identified work packages. As a result, every single work package was at least matched with two competent companies providing redundancy and de-risking initial development efforts wherein partner companies actively participated alongside MİLTEKSAN's own employees. Right after MİLTEKSAN's formation an advisory committee across the globe comprising of world renowned scientists was formed to guide and oversee research and development activities. Consequently, MİLTEKSAN initiative has become a role-model for coordination between industry, government, industry clusters and academia.

Figure 8. A Scene From SAHA-Istanbul Sub-Comittee Meetings on CNC Controller Development in late 2019.

For the domestic machine tools industry, the profit multiplier is expected increase with an indigenous new generation CNC controller, which will create high added value, in line with the expectations of industry and government. Moreover, as an important contribution, since the intermediate product needs of high value-added sectors shall be met by domestic means, production shall be possible without being subject to export restrictions. A domestic CNC controller shall provide import substitution as well. From this point of view, it will contribute to the production of CNC control equipment that Turkey needs. Furthermore, thanks to the high multiplier effect, not only the project output is with the product; An indigenous CNC controller will create a positive multiplier effect by increasing the product development capabilities and capacities in the defense industry, medical industry and other high value-added industries.

Progress in Building a New Generation CNC Controller

Domestic new generation CNC controller development encompasses both hardware and software development. Progress in both is briefly discussed in this section.

Hardware Development: MİLTEKSAN's CNC controller shall be IPC based. EtherCAT was chosen as the field bus solution of MILTEKSAN Controller. IPC shall act as the EtherCAT (Ethernet for control automation technology) master. Servo-motors and I/O modules shall be the slaves. Note that ethernet is not optimized to send short, frequent messages. Moreover, the commonly used star topology for switched ethernet leads to excessive cabling and highly cascaded communication dependencies. EtherCAT addresses these shortcomings and from an Ethernet point of view, an EtherCAT bus is simply a single large Ethernet device that sends and receives Ethernet telegrams [Jansen and Buttner, 2004]. Hardware development efforts are initially focused on developing an industrial PC (IPC) as shown in Figure 9 and I/O modules such as the one shown in Figure 10. Thereafter, a touchscreen and a wireless hand-wheel will also be developed. Indigenous servo-motors and drivers designed and built in Turkey will be used in the overall system. In order not to duplicate efforts existing hardware solutions shall be harmonized with MİLTEKSAN software. Servo-driver software shall support CiA-402 standard and will communicate with the IPC over the EtherCAT bus. SOME (2019) is used as the EtherCAT master stack library.

Figure 9. Conceptual Design of MİLTEKSAN Industrial PC (Image courtesy of PAVOTEK).

Conceptual design of MİLTEKSAN IPC is shown in Figure 9. Technical specifications of the IPC are listed below.

- Intel® Core™ i7-8665UE, Quad Core, 1.7GHz

- 8 GB DDR4 RAM
- 32 GB SSD
- 3 x Gigabit Ethernet
- 1 x Display Port
- 24 VDC
- 80 mm x 152 mm x 108 mm

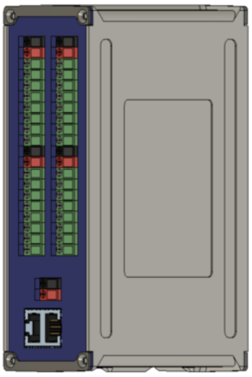

Figure 10. Conceptual Design of EtherCAT I/O Modules (Image courtesy of PAVOTEK).

EtherCAT I/O modules shown in Figure 10 shall be manufactured in six different configurations as outlined in Table 4.

Table 4. I/O Module Configurations.

Configuration	Specification
1	8 x Digital Input/Output
2	16 x Digital Input/Output
3	4 x Analog Input/Output
4	8 x Analog Input/Output
5	3 x Encoder Input
6	6 x Encoder Input

Software Development: Figure 11 shows the top-level architecture of MİLTEKSAN CNC controller software. As seen here time-critical tasks are run within a real-time Linux operating system. This operating system is customized version of Linux-RT using Yocto Project (2010) and named as MİLTEKSAN-RT. Primary software development language is modern C++.

User interface communicates with the controller software through a gateway using protocol buffers via a TCP socket. Mobile devices and web interface also communicates via the same infrastructure reducing development efforts and avoiding redundancy.

Motion control module commands servo-drivers. All axes are controlled according to motion control standards by means of software implemented on EtherCAT Master according to DS-402 standards. Figure 12 shows some test results from simultaneous interpolation and multi-axis motion control tests.

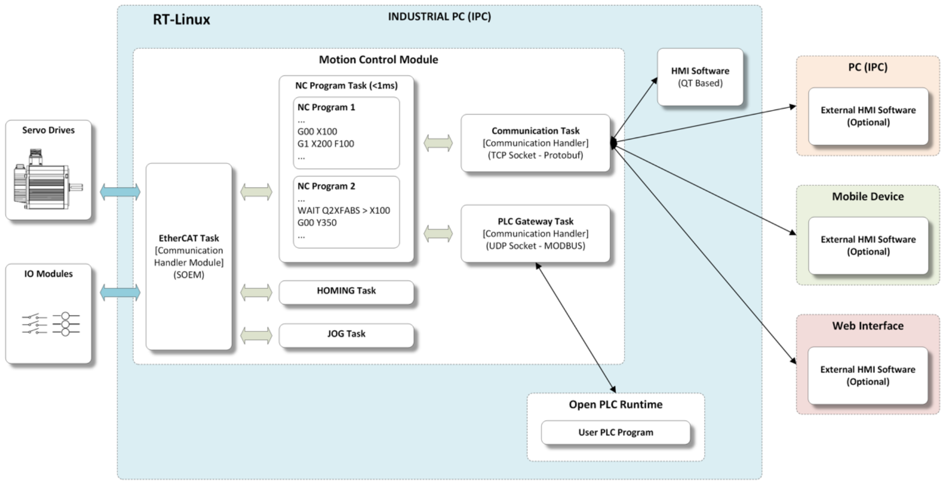

Figure 11. Top Level Architecture of MİLTEKSAN CNC Controller Software.

Motion control is defined as per G-codes. An in-house developed interpreter is used in the motion control module. G-codes are standardized, whereas M-codes (machine codes) are machine specific and are defined by the machine manufacturer during commissioning phase. M-codes are executed by a soft-PLC in our architecture. OpenPLC runtime [Alves, 2022] executes this user-defined logic synchronously with the motion control module.

PLC logic is defined by the machine manufacturer using one of the IEC 61131:3 languages in an editor as shown in Figure 13. Note that IEC 61131-3:2013 specifies the syntax and semantics of a unified suite of programming languages for programmable controllers. This suite consists of two textual languages, Instruction List and Structured Text, and two graphical languages, Ladder Diagram and Function Block Diagram [Tiegelkamp and John, 2010].

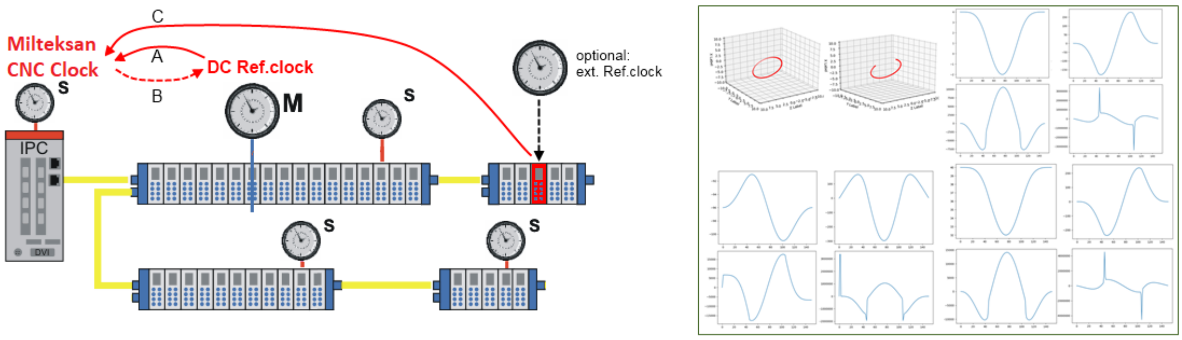

Figure 12. Synchronous CNC Motion Control Procedure.

These programs written in IEC 61131 are translated into C language by an open source compiler MATIEC developed by de Sousa (2003) and linked against PLC tasks shown in Figure 11 and compiled into machine language.

OpenPLC communicates with the physical world via ModBus protocol whereas MİLTEKSAN CNC controller ultimately uses EtherCAT bus. To bridge gap Socket API is used and I/O variables are mapped between ModBus and EtherCAT bus, much the same way as Lin and Cheng did in their 2018 study [Lin and Cheng, 2018]. This approach is quite convenient and does not require any modification in the internal workings of neither OpenPLC nor MİLTEKSAN's proprietary controller software.

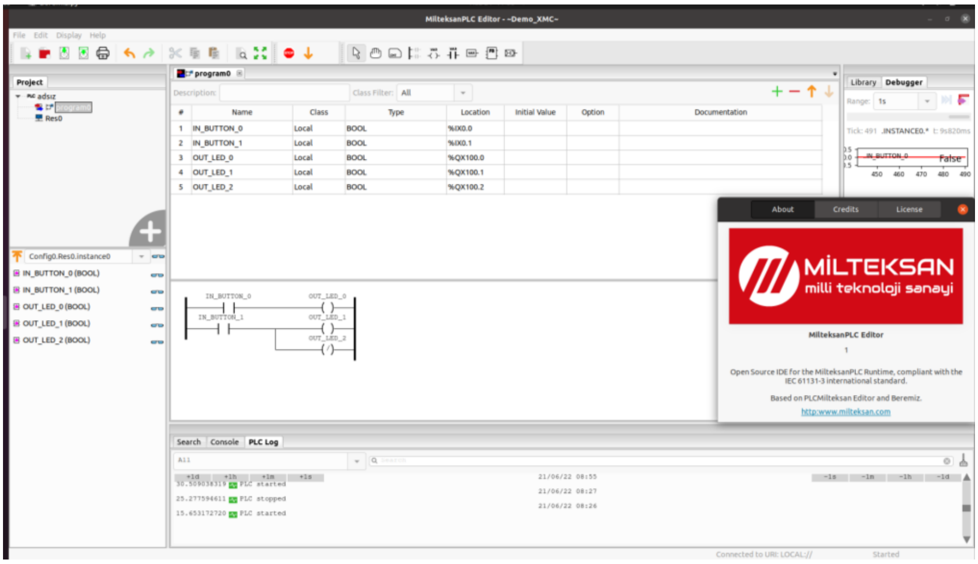

Figure 13. PLC Editor User Interface.

Having laid out the software architecture next step is performing the cutting process. Trajectory generation and system identification modules were developed for a three-axis machine. Cutting tool trajectory generation is critical in precision machining of work-piece on machine tools. The generated tool path can trigger the natural frequencies of the machine tool and servo-motor system and interfere with precision machining. Therefore, the generated tool path should not only give the desired path, but also the required continuity. It is usual for natural frequencies to be triggered if velocity and acceleration continuity is not maintained at the junction of consecutive segments. The tool path algorithm developed in this study can perform linear and circular interpolation by operating at the time of the servo-motor control loop. In addition, the algorithm provides C^3 continuity by generating micro-curves between consecutive segments, regardless of linear or circular. This allows rapid and smooth transition between segments. Micro curves used in the transition regions between segments in the tool path algorithm are created using a fifth degree polynomial with limited acceleration and jerk. Circular and linear tool paths generated outside the transition zones are generated with a trapezoidal acceleration profile with jerk limit [Kahraman et al., 2022].

Figure 14. A View From 3-Axis Test Bench.

In order to validate developed software bechtop experiments were carried out before mounting servo-motors onto the test rig. Figure 15 shows an instance from these tests.

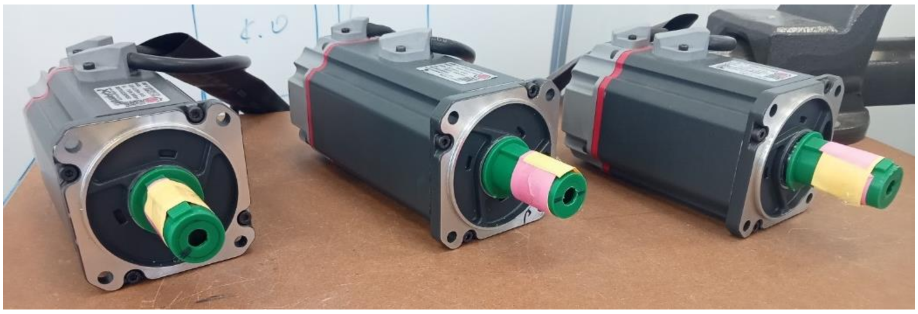

Figure 15. A View From Bechtop 3 Axis Simultaneous Interpolation Tests.

Furthermore, system identification is realized for a 3-axis Gantry type test machine equivalent moment of inertia, viscous and Coulomb friction parameters are estimated. Frequency response functions of axes are obtained from torque excitation signal and gathered velocity data. Previously estimated parameters and these FRF values are also compared. These studies shall constitute the basis for auto-tuning module for the axis control parameters [Demir et al., 2022].

Final goal is to perform five-axis simultaneous interpolation along with volumetric compensation. Extension of trajectory generation algorithms and volumetric compensation is presently an ongoing effort. To achieve this goal the approach outlined in Xiang and Altıntaş (2016) as illustrated as a flowchart in Figure 16 is anticipated to be followed.

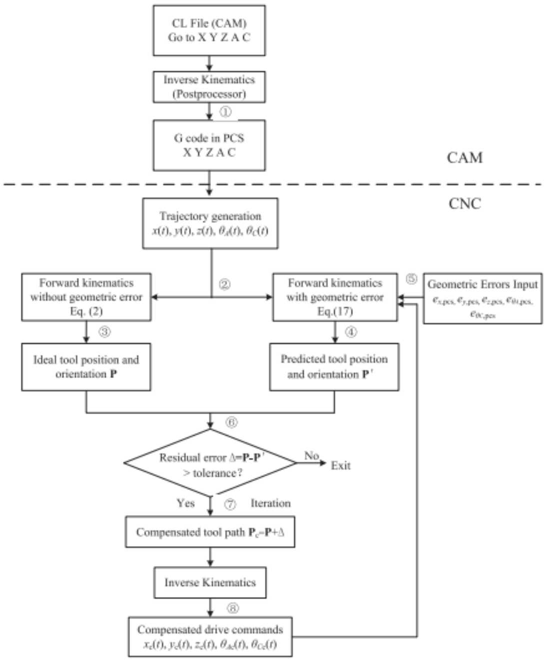

Figure 16. Flowchart of 5 Axis Motion Control with Volumetric Compensation [Xiang and Altıntaş, 2016].

5. CONCLUSION

CNC controllers are used in mother-machines (i.e. machines that make other machines) and they are strategic products for any country that wishes to maintain a healthy machine manufacturing industry. Turkish machinery sector is aiming to increase the value per unit mass up to 15 USD/kilogram. The present era of digital transformation has brought opportunites to develop new generation CNC controllers with fewer technological barriers to enter into the market. Industrial PC based controllers and high-speed data bus architectures enable flexibility in terms of hardware eliminating the need for developing dedicated electronics. Value added is significantly shifting towards software and this trend is expected to continue. MİLTEKSAN initiative is developing an indigenous new generation CNC controllerto capitalize on this opportunity.

Timing is right for a new initative to develop CNC controllers and enter into the market. On the other hand, the competition structure of the market is oligopolistic. There exist barriers for market entry in this regard. Sunk costs such and research and development costs need to be met by investors. In order to reduce sunk cost burden and to obtain market traction, support from industry cluster organizations and relevant government entities is crucial. The way that MİLTEKSAN initiative was formed and currently operating can be a role model for many other high tech initiatives. Only than the machinery sector can perform a full-scale digital transformation.

MİLTEKSAN's new generation CNC controller development efforts in terms of hardware and software were briefly quoted. A three-axis proof-of-concept demonstration was achieved using in-house developed controller software. This includes a G-code parser, trajectory generator, communication gateway, user interface. These components run on a custom real-time Linux flavor called MILTEKSAN-RT. A seperate digital-twin software was also developed to in order to simulate chip removel process. Presently near real-time simulation capability is achieved with the digital-twin software. To this date conceptual design of CNC controller hardware has been finished.

Prospective studies include manufacturing and testing the aforementioned hardware (IPC and I/O modules) and a full five-axis technology demonstration using the test rig shown below in Figure 17.

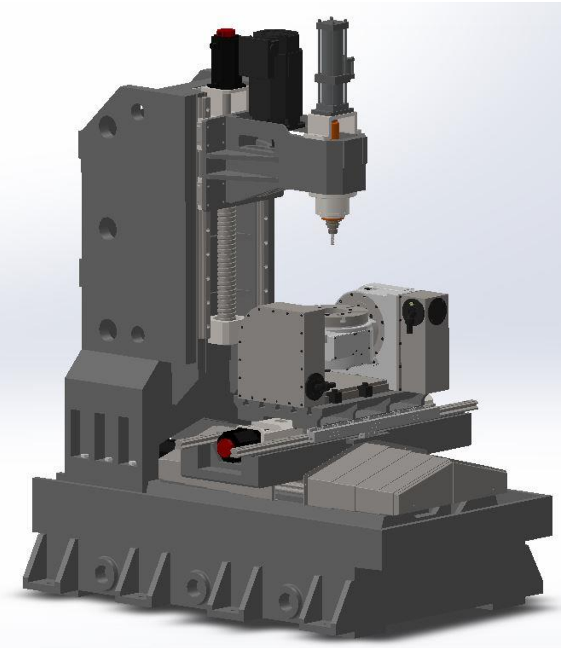

Figure 17. Solid Modelling of Prospective 5 Axis Test Rig.

This test rig is currently being manufactured and assembled. Findings will be shared in the upcoming UMTIK conferences. Development of a collision detection module is also within the scope of prospective studies.

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