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New trends in the design of human-machine interaction for CNC machines

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Abstract: The development of numerical control technology, the increasing efficiency of production processes and the high automation level have allowed a great improvement of Computer Numerical Control (CNC) machines. Although CNC machines allow short working times and the precise repeatability of the processing, they suffer from some major disadvantages: they need to be controlled and managed by an expert operator who has to interact with the user interface to complete her/his tasks and set-up the machine. Unfortunately, to the best of our knowledge, there are no thorough studies on how human operators manage and perceive the interaction with these machines. As a result, the interfaces of most current CNC machines present several limitations. Considering the advantages in adding ergonomics and usability analysis to increase quality, productivity and market competitiveness, the industrial world is moving to develop new interfaces for CNC machines, to improve users' experience. Starting from our experience with woodworking CNC machines, this paper reports, first, an analysis of the CNC process from the point of view of human-machine interaction; specifically, main issues and criticalities are outlined. Then, major new trends in modern interfaces for CNC machines are presented, highlighting the tendency to integrate user experience in the design of interfaces.

Keywords: Human-machine interface, User interfaces, Man/machine systems

1. INTRODUCTION

CNC machines have gradually become the core of the equipment manufacturing industry, attracting high attention from many machine tool manufacturing companies, and have introduced great competitiveness in several modern manufacturing fields. The acronym CNC stands for "Computer Numerical Control" and means that an internal electronic device, integrated in the machine, is responsible for controlling the movements and the functions of the machine during the process, depending on a well-defined work program.

CNC machines have surpassed the traditional machines in which the movement is manually driven by an operator, who defines the quality of the piece and the machine performances. In a traditional process, the quality of production depends on different factors such as manual piece fixing and unloading, human attention, processing speed, the machine itself, etc.

The evolution of CNC machines has led to an increase in the performance and the independence of the piece quality with respect to the operator. Compared to manual machines, other advantages offered by CNC machines are highly reduced working times and the precise repeatability of the processing, which allow to decrease the unit costs of production and obtain an higher and more uniform quality. Moreover, they eliminate the position error and they reduce the dead time due to manual movements. In addition, CNC machines are equipped with adjustable heads (inclinable axes) able to rotate gyroscopically along two axes. This allows to incline the tool according to all work surfaces and makes it possible to create very complex surfaces and geometries, with high tolerance and precision, which are difficult to obtain with manual processing.

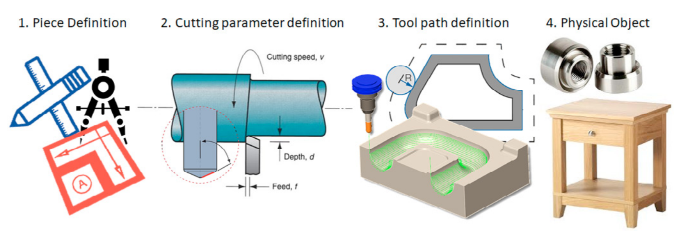

Fig. 1. CNC machine production phases.

As Fig. 1 shows, the main phases of programming a CNC machine production are: piece definition, i.e. realisation of the 3D drawing and definition of where to position the part, analysis of the processing steps and determination of the cutting parameters, tool path definition, i.e. definition of the movements performed by axes and tools, and realization of the physical object.

CNC machines are therefore made of mechanical and technological parts and of software components, such as CAD and CAM software. CAD (Computer Aided Design) software refers to the tools that have gradually replaced manual design. It allows the generation of the 3D drawing of the pieces to be realised. CAM (Computer Aided Manufacturing) software, on the other hand, refers to the programs that define tool path and instructions that can be interpreted as tool movements by the machine

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controller. A set of instructions builds a CNC program that, thanks to CAM software, is translated by the CNC machine into real movements performed by axes and tools. ISO 6983 standard provides a standardized data format for positioning, line motion and contouring control systems for all CNC machines programming, relying on establishes G code or ISO code (Xu and He, 2004). Thanks to this unified language, the same program is compatible with different machines; hence, homogeneity of behaviours and processes can be achieved, and margins of uncertainty are reduced.

Thanks to this structure, flexibility becomes one of the main advantages of CNC machines: with just one machine, often with the same tools, it is possible to switch among different processes almost instantaneously (Rossi and Maiocchi, 2014; Grimaldi, 2007).

1.1 Applications of CNC machines in carpentry

Given the extreme versatility, accuracy and ability to process many materials such as wood, iron, plastic, polyurethane and light metals, CNC technologies have been applied and adopted in many production sectors such as carpentry, sailing, upholstery, packaging and material handling (Lähtinen et al., 2007).

The core of CNC machines is carpentry, an integrated economic chain from raw material to finished products. This sector is linked to the specificity of the raw material, the requirements for environmental protection and the sustainable use of resources. CNC machines are in use particularly when various wood species need to be machined, often in combination with other materials, such as plastics or non-ferrous metals. Solid wood or wood materials, such as plywood, particle board or panels, can be milled, sawed or sanded automatically and in series production. CNC machines permit to produce construction elements (doors, windows, etc.), for solid wood processing (furniture, interior design), and for panel machining (Assessorato Agricoltura e Risorse Naturali Alto Adige, 2015; Bernetti and Romano, 2007).

Typical woodworking processes are:

- production of half-processed products (cutting of the trunk, drying, etc.),
- second transformation (half-processed work),
- surface finishing (lacquering, painting, etc.).

Further, some specific tasks, especially for second transformation, are:

- cutting, normally first phase of wood processing, necessary to cut the panel to the measure required by the project,
- planing, necessary to make the wooden panel faces linear, parallel and of the necessary thickness,
- milling, for removing the material to obtain a wide range of surfaces,
- drilling, allowing to make holes and buttonholes essential in many objects and furniture to insert hinges and locks,
- sanding, for obtaining surfaces ready for the finishing phases.

Such a variety of processes and tasks highlights how diversified this industry is. In this regard, the use of CNC technology is advantageous since it is flexible and can be adapted in different constructive fields, for different kinds of materials and work functions. Nevertheless, such variability is not specific of wood industry, but can be found in many other domains where CNC machines are used.

1.2 Human-machine interaction in CNC machines

Despite the above mentioned advantages brought by CNC machine tools, they suffer from several disadvantages. In particular, their versatility typically implies that their management and control is quite complex. Indeed, they must be controlled by an operator who is in charge of setting up the program, preparing the blanks to be processed and taking proper action in case of problems or corrections in processing. Users have to constantly interact with the machine to complete common tasks (as setting up the machine and preparing the pieces to work), and to monitor and manage the production.

These activities are performed by means of computerised human-machine interfaces (HMIs) that are inevitably becoming more and more complex as new functions are implemented in machine tools. In this new scenario, human operators experience many difficulties to interact efficiently with the machine. For example, in addition to supervising the process during normal work production activity, operators have to carry out many activities to support the work cycle, including loading the program, positioning and preparing the raw pieces, the surfaces and the tools necessary for a specific program. Moreover, in addition to the different activities, a CNC machine has to control various types of material, from the hardest to the softest. To obtain an optimal result, it is necessary to correctly choose the cutting speeds and the type of tool to be used for the specific task at hand.

As a consequence, to improve efficiency, increasing working speed and machine tolerance is not any more sufficient; as well, it is important to increase operator's comfort by providing her/him properly designed HMIs (Sonderegger and Sauer, 2010). Specifically, a well designed interface helps in reducing the time required to perform a task and the errors, by presenting information in a clear and timely manner. In addition, a simple and structured HMI allows less specialised users to manage the process, avoiding wrong decisions or increasing situation awareness (Adikari and McDonald, 2006).

Consequently, studies on human-machine interaction in the design of interfaces are needed to increase quality, productivity and market competitiveness, especially when large-scale projects, new materials, new structures, and new technologies emerge. Unfortunately, most of recent studies and research on HMIs are focused on the design of HMI of large control equipment; only few studies and analyses focus on CNC sectors.

Starting from an analysis on wood industry sector, the aim of this paper is to present the characteristics of HMIs for CNC machines, discussing how industries have been addressing some critical issues in the interaction between operators and the machine, to understand how to continue developing these machines to make them even more productive.

In the following sections, first, an introduction of usability and ergonomic principles is shown in Sec. 2 to highlight the main advantages and understand why research first and industries then have interested in those fields. Second, we report the results of our survey carried out with major producers of CNC machines for the woodworking sector. In particular, in Sec. 3 we discuss the main criticalities reported for current generation CNC tools with specific regard to human-machine interaction. Then, the new trends in modern interfaces for next generation CNC machine tools are outlined in Sec. 4, as described by the interviewed companies. The reported considerations have general validity and apply to the other industrial sectors where CNC technology is used. Finally, we point out some concluding remarks in Sec. 5.

2. ERGONOMICS AND USABILITY IN HUMAN-MACHINE INTERACTION

A well-designed HMI addresses operators' needs and difficulties by providing support in a form that is easy to understand and effective. To this end, the application of usability and ergonomics principles makes the interaction between the operator and the machine as simple as possible, thus facilitating and improving performance, productivity and work efficiency. In addition, the interface becomes structured and simple allowing to accomplish and manage the process and guide the user along working activities (Schaffer, 2004).

Contrariwise, poorly designed interfaces might lead to bad decisions or incorrect behaviours from the users, abnormal situations with machines and plants, billions of dollars of lost production, accidents and casualties. The error of an operator is undoubtedly the most important cause of many accidents and many of them come from the lack of awareness of the situation.

Studies and researches of usability and ergonomics principles for the design of appropriate interaction tools have made their way among the classical disciplines of engineering, earning a place of great importance in many industrial sectors.

According to ISO 9241-11:2018 (ISO, 2018), usability is defined as the degree to which a product can be used to achieve certain objectives with effectiveness, efficiency and satisfaction in a specific context of use. It relates to the effort required by users to understand and use the system and operate successfully.

The ISO 26800 (ISO, 2011) defines ergonomics has the scientific discipline concerned the understanding of the interactions among human and other elements of a system (human or other). Ergonomics studies theory, principles, and methods to design and optimise human well-being and overall system performance and satisfaction. It relates to the quality of the relationship between users and machines.

As a consequences, ergonomics and usability are multidisciplinary branches that require skills in various fields, both technological and human, such as computer science, operating systems, programming languages, developing environments, communication theory, design, graphic and industrial design disciplines, linguistics, social sciences, cognitive psychology, human performance, engineering, etc.

To create a usable product it is necessary to consider functional requirements and, in addition, take into account cognitive aspects of human processing. This should be achieved also by keeping in constant contact with users, their contexts of use, their desires, their skills and their needs. In the design of a product, it is therefore very important to involve users and customers since the initial phases of planning and prototypal design, for understanding how the activities are carried out.

3. CRITICALITES IN HUMAN-MACHINE INTERACTION FOR CURRENT CNC MACHINING

We carried out a systematic analysis to detect the main critical issues of CNC interfaces, from the point of view of human-machine interaction. Our analysis focused on woodworking industry and the HMIs of four major producers of woodworking CNC machines (two from Italy and two from Germany) were considered. However, the issues found have general validity and apply also to other manufacturing sectors since the need of an expert user to control and manage the process is typical in all CNC machines' sectors.

As discussed in the following, the critical issues found could be summarised as:

A. not suitable support information,
B. alternation between panel and machine,
C. non-homogeneity of presented information,
D. user's tasks not focusing on production functions.

3.1 Not suitable support information

As manufacturing systems relying on CNC technology increase in sophistication and complexity, a considerable amount of information is required for plant operation and maintenance. When user's cognitive effort increases, errors or faults could happen. To restore normal working conditions in a safe, easy and quick way, human operators would benefit from proper guidance and suitable support information.

Typically, troubleshooting support consists in a manual collecting printed one-point lessons that briefly resume the steps necessary to solve a specific failure. However, these do not ensure ubiquitous access to information, direct access to the current state of the machine and evidence of the logical links existing between different pieces of information (Villani et al., 2016).

Moreover, conventional manuals exhibit a hierarchical structure that does not facilitate the extraction of desired contents and the retrieval of the interrelationship between them. They usually suffer from redundancy which is detrimental for both who is in charge of editing documentation and users. Other problems include lack of direct communication between users and manufacturers or suppliers, disorientation effect of a large amount of information and high costs to update content.

These criticalities lead to the tendency to discard such manuals and, rather, contact technicians, supervisors or support for helping, with a consequent loss of time and money and decline in performance and productivities.

3.2 Alternation between panel and machine

Despite a high level of flexibility and complexity in CNC machines, there are several functions that need the intervention of the operator to set-up the machine and the pieces to work. Normally, the machine configuration involves tools preparation, work plan arrangement and software updating related to machine structure.

Accordingly, the user has to perform a series of operations alternating between the operation panel and the machine. She/he has to move physically from the panel, to check the information, to the machine, to perform the functions, and then again to the application to confirm the operation done. This alternation can create errors and increases the cognitive effort of the user.

As an example, let us focus on the tool change procedure. Tool preparation is one of the most critical operations at the level of control, prevention and supervision of process errors. The procedure for changing a tool and managing the tool holder carousel for a specific procedure requires the following steps to be taken at the physical tool warehouse and at the control panel to set the virtual warehouse: recognising the tools needed for the next working task, loading CAD drawings of new tools and CAM paths at the machine panel, setting the process interacting with the machine panel, removing previously used tools from the tool holder carousel, identifying available positions on the tool holder, virtually choosing and defining the new position on the panel, physically positioning the new tools in the tool holder carousel matching the positions selected on the machine panel, virtually saving the new carousel structure and starting the process clicking on start cycle button. Moreover, the operator has to prepare the workbench, positioning the raw piece and the stopper suction cups, in accordance with the CAM paths and the HMI instructions. In this sequence of operations, typically problems arise since physical operations on the machine are not mapped on-line in the software application, with a consequent lack of consistence between the status of the machine and information presented in the interface.

This procedure is highly prone to errors because it requires high cognitive effort, memory and attention of the user, due to continue alternation between the HMI and the machine to complete the task. For example, a different tool could be loaded and therefore with different dimensions or working parameters not coherent for the current process, machine and material. Furthermore, the user could forget to mount the physical tool on the machine, load the tool CAD drawing of a different tool, or choose a different position on the carousel compared to the one in the software.

3.3 Non-homogeneity of presented information

Given the extreme versatility, accuracy and the ability to perform specific and different functions, CNC production lines are composed by a variety of different machines. As an example, it is likely to find work centers for lathe and milling machines to define the geometry of the piece, beading machines to realise the edge of the component, drilling machines, etc.

Although being based on the same technology, in typical settings such machines exhibit highly diversified user interfaces, where similar pieces of information are presented differently, in a non-homogeneous manner. Lack of standardization implies higher learning curve because no common principles and methods are metabolised over time. During the management of the various phases of production, the operator interacts with different machines which present different organisation of information, design and interaction methods. The possibility of errors increases because her/his behaviour is not stratified but she/he has to adapt and coordinate with the machine each time.

This aspect becomes more relevant particularly in little industries where the same operator has to manage different machines, and thus has to be flexible to adapt to different representations of the same working task.

3.4 User's tasks not focusing on production functions

In addition to supervising the process, during the normal work production, the user has to carry out many activities to support the work cycle. Often, she/he has to deal with the machine's program, modify the CAD-CAM drawing in the control panel and choose appropriate tools and working parameters.

Thus, operators of CNC machines need different, specialised and wide skills, often distant to the ability normally required to operators in other industrial sectors. Specifically, operators of CNC processes need basic knowledge of ISO code, simulation and 3D software programming, to adapt the production to a specific request, material or machine. As a consequence, expert specialised operators are difficult to find and training of non expert ones implies high costs.

4. NEW TRENDS FOR HMIS IN CNC MACHINES

Considering ergonomics and usability analyses in the design of CNC machine tools becomes necessary to address the critical issues presented in the previous section. Due to new interaction technologies, a new generation of HMIs for CNC has started to improve performance, efficiency, and safety of work. The goal is to privilege in the design of human-machine interaction the role of use and user.

The above mentioned leader companies for woodworking have been interviewed also in this regard. In particular, we interviewed them with respect to the main drivers that are guiding the design of their next generation CNC machines. Such main trends in HMIs for CNC machines can be summarised as follows:

A. service tool application,
B. portable interfaces,
C. standardisation in layout and style,
D. connection between engineering department and production line,
E. user-centered design.

4.1 Service tool application

To keep machines running as much as possible and increase production efficiency, it is necessary to assist rapidly customers in the case of machine stop, by providing operators with the necessary assistance. Moreover, industries want to guarantee continuative service (i.e., 24 hours per day, 7 days per week), in order to decrease costs related to machine stop.

As mentioned in Subsec. 3.1 and in (Villani et al., 2016), the usual troubleshooting methods suffer from some limitations, especially when a technician is needed physically on the production line. To overcome such limitations, current trends consist in the integration in the HMI of an application to remotely connect to the machine control panel, in order to allow direct and fast communication with operators, tracking all previous activities to frame the current situation and suggest a straightforward solution.

Storing the history of interaction allows to check the progress on a machine and record anomalies and needs for ordinary or extraordinary operations. From the service point of view, such an application can extract content to create databases, and find, for example, repeatable anomalies and anticipate them (Fig. 2). Moreover, the application can be used to make video-calls and send images providing clear evidence of errors or specific data. The physical presence of a technician can be replace with a new and faster communication system.

Fig. 2. Service tool application to assist rapidly customer.

4.2 Portable interfaces

To decrease human error due to the physical alternation between the panel and the machine, described in Subsec. 3.2, industries have started two different kinds of approaches.

First, when a new tool CAD drawing is loaded on the panel, to avoid confusion and disorientation, and to allow easier tools and pieces recognition, a 3D image preview and its relative main parameters are shown. Moreover, messages and software controls are added when the user has virtually loaded the piece or changed some tools or configuration, to check that these actions are actually carried out on the machine.

Second, to prevent mistakes and eliminate user's physical movements from the panel to the machine, industries have begun to develop portable devices that communicate with the machine in wireless way. As shown in Fig. 3, the device is designed to present the same functionalities as in the work panel of the machine. This reduces the time to perform activities and the cognitive load of the operator, who can then perform tasks, such as tool change, without memorising codes, carousel positions, or other different kind of data.

Fig. 3. HMI portable device designed to present the same functionalities as the ones on the machine panel.

4.3 Standardisation in layout and style

In this trend the idea is to arrange the information in the HMI of different machines of the same industry in the same way, addressing the criticality explained in 3.3.

The goal starts from following and realising a responsive design, that, as shown in Fig. 4, allows desktop information to be viewed in a coherent manner in response to the size of the screen or web browser one is viewing with. In this way, the same application, especially if new portable HMIs are created, is shown in a clear and accessible form, considering many factors from device properties to user characteristics, such as cognitive abilities, vision skills, physical impairments, etc.

Further, the most important idea is that of having different devices with the same layout. Consistency, unification and organisation of contents for different production systems and machines are guaranteed, to fit in the same place the similar pieces of information in any device. Hence, users can easily find all the information, even when she/he switches rapidly between the management of different processes.

Consistency and ease of use become the goals, and, as a consequence, in the entire project the brand and company style emerge, creating a family feeling for the brand, and people perceive cooperation among the members of an organization.

Fig. 4. Responsive design and consistency of layout.

4.4 Connecting engineering department and production line

As Fig. 5 shows, to limit the variety of skills and abilities required to a CNC operator and avoid errors, the idea is to split tasks between the engineering department and the operator in the production line. In this way, shopfloor operators do not have to deal with the machine program and the choice of appropriate tools and working parameters, as underlined in Subsec. 3.4, but they can focus their attention only on specific aspects of production.

In addition, if the order is sent directly from the office, already designed by engineers, the production would become faster and optimised, and the technical office would be able to control the production and manage the process priorities. Moreover, following this trend, human errors and operator's required skills are reduced.

Fig. 5. The technical office designs and sends request of production, while shopfloor operators focus their work on production related activities.

4.5 User-centered design

A common basis to the trends identified above consists in grounding the design of new generation user interfaces to users' experience. In other words, the importance of building the design upon users' needs and feedback is now being appreciated also at industrial level, and is finally moving from theoretical recommendations and guidelines to concrete practical approaches. As Fig. 6 shows, to help the identification of any problems associated with the design of user interfaces, it is important to take into account user experience aspects both in feedforward in the design phases and as a feedback, in the review process. These aspects must be considered jointly in conjunction with efficiency related requirements.

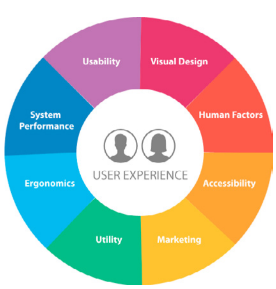

Fig. 6. Keeping in constant contact with end users and their point of view to identify problems associated with the design of interfaces.

These general thoughts are confirmed by the fact that, among the industries leaders in the woodworking sector surveyed for this paper, three out of four declared to have conducted a usability study involving their customers to derive requirements for their new generation HMIs. Specifically, they have used questionnaires to make users' complaints in the usual context to continue innovate the systems. Moreover, a direct observation of how operators interact with the application has been done to identify the related problems and the user's preferences.

5. CONCLUSION

In this paper, starting form a systematic analysis in wood CNC sectors, a description of the CNC process for human machine interaction point of view was presented, to outline critical issues and characteristics. The processing performances of CNC machine tools are becoming more and more high thanks to the development of numerical control technology and the improvement of processing efficiency and automation level. Despite such characteristics, human operators still work in close cooperation with the machine to control and supervise its functions. For the interest to improve performances and productivity, industries gradually realise that is not sufficient to increase work speed and machine tolerance. It is important to assist operators during their work activities and increase their comfort by providing properly designed HMIs. In this paper, new trends in modern interfaces for CNC machine sectors were described, to highlight the tendency to integrate user experience in the design of the interfaces.

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REFERENCES

(2011). ISO 26800:2011. ergonomics – general approach, principles and concepts. *ISO/TC 159/SC 1 General ergonomics principles. International Standardization Organization (ISO).*

(2018). ISO 9241-11:2018. ergonomics of human system interaction – part 11: Usability: Definitions and concepts. *ISO/TC 159/SC 4 Ergonomics of human-system interaction. International Standardization Organization (ISO).*

Adikari, S. and McDonald, C. (2006). User and usability modeling for HCI/HMI: a research design. In *Information and Automation, 2006. ICIA 2006. International Conference on*, 151–154. IEEE.

Assessorato Agricoltura e Risorse Naturali Alto Adige (2015). Legno: rafforzare la nostra risorsa.

Bernetti, I. and Romano, S. (2007). *Economia delle risorse forestali.* Liguori Editore Srl.

Grimaldi, F. (2007). *Manuale delle macchine utensili a CNC: torni, centri di lavoro, elettroerosione, ultrasuoni, laser, plasma, getto d'acqua.* Hoepli.

Lähtinen, K. et al. (2007). Linking resource-based view with business economics of woodworking industry: earlier findings and future insights.

Rossi, M. and Maiocchi, B. (2014). *Manuale delle macchine utensili.* Tecniche nuove.

Schaffer, E. (2004). *Institutionalization of usability: a step-by-step guide.* Addison-Wesley Professional.

Sonderegger, A. and Sauer, J. (2010). The influence of design aesthetics in usability testing: Effects on user performance and perceived usability. *Applied ergonomics*, 41(3), 403–410.

Villani, V., Battilani, N., Lotti, G., and Fantuzzi, C. (2016). MyAID: a troubleshooting application for supporting human operators in industrial environment. *IFAC-PapersOnLine*, 49(19), 391–396.

Xu, X. and He, Q. (2004). Striving for a total integration of CAD, CAPP, CAM and CNC. *Robotics and Computer-Integrated Manufacturing*, 20(2), 101–109.