Design of a user-friendly human machine interface for jet electrochemical machining

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Abstract. Electrochemical machining with a closed free jet (Jet-ECM) is a flexible ablating manufacturing technology. With this manufacturing technology, surface structures in the micrometer range can be generated without tool wear occurring. Until now, the technology has mainly been developed in research institutions. Therefore, the aspect of a user-friendly human machine interface has not been in the focus of the machine tool design. The aspect of a user-friendly human machine interface was considered in the construction and development of a new Jet-ECM prototype system at the Otto von Guericke University Magdeburg (OVGU). The prototype system is intended for teaching and research purposes. Users, who will operate the prototype system, have different knowledge of the Jet-ECM process and machine control. Therefore, it was necessary to develop a user-friendly interface, that is easy to learn and easy to use.In the present study, the procedure for creating a user-friendly human-machine interface will be introduced, and the resulting design will be explained. The design was developed according to established design guidelines for machine systems and can also serve as a template for industrial operation. To arrange the operating elements ergonomically and according to the material, energy and information flow, a suitable mask layout was developed. Furthermore, the user interface is suitable for future expansion. Based on the realised user interface, the main components of the Jet-ECM prototype system can be controlled, various process functions can be executed, and different process variables can be analysed.

Introduction

To create a graphical user interface (GUI) for Jet-ECM, the fundamental understanding of this manufacturing technology is necessary to conduct various user tasks. Jet-ECM is an electrochemical machining process based on the anodic dissolution of the workpiece under the influence of electric charge exchange [1,2]. The dissolution takes place between the workpiece and the liquid ion conductor, called electrolyte. Reaction products are carried out by the continuous electrolyte flow. In Jet-ECM an electrolyte jet localises the electric direct current between the anodic workpiece and the cathodic tool, as seen in Fig. 1. The nozzle is positioned at a defined position above the workpiece surface. This nozzle is made of stainless steel and has an inner diameter of e.g. 100 µm [3]. An electrolyte is pumped through the nozzle and hits perpendicular upon the surface of the workpiece. The ejecting jet is forming a closed free jet, because there is no mixing between the surrounding fluid and the ejecting jet, due to the lower density of the atmospheric air in comparison to the electrolyte [4].

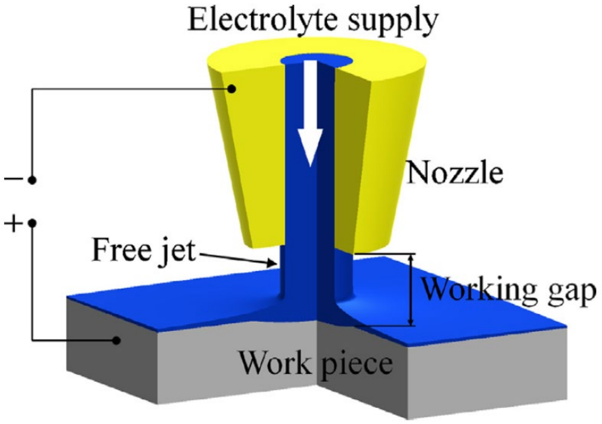
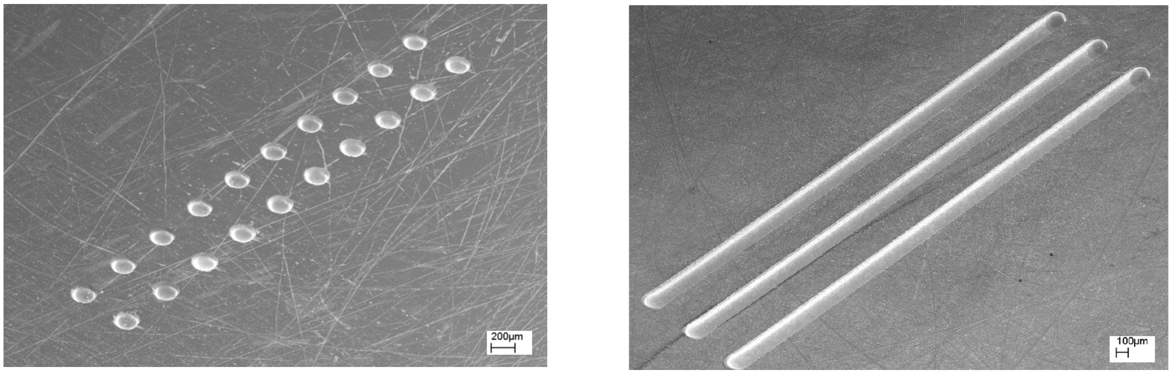


Fig. 1. Scheme of Jet-ECM [3].

The current density, which amounts up to 1000 A/cm², is localised due to the shape of the closed free jet [5]. Therefore, a high localisation and a high precision of the removal geometry can be achieved. Different removal geometries can be realised by changing the movement strategies of the nozzle and the on-time of the electric current.

Machined examples are shown in Fig. 2 and Fig. 3. Without movement of the nozzle in the machining process, point removals can be generated. The depth of a point removal depends mainly on the on-time of electric current. An array of point removals shows Fig. 2a). The shape of a point removal is a typical calotte geometry.



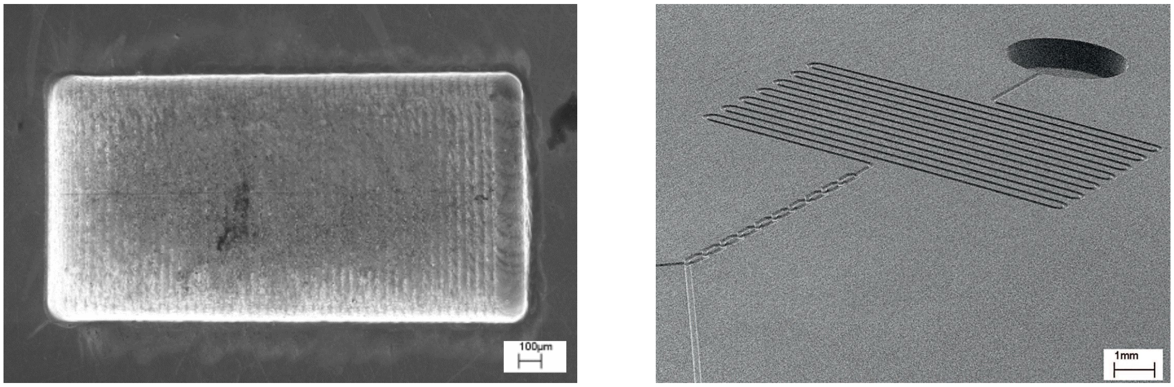
a) Point removals b) Line removals

Fig. 2. SEM images of point and line removals generated with Jet-ECM [6].

With movement of the nozzle and constant process parameters, different forms of removal geometries can be machined, such as line removals, plane surfaces and contour removals. Line removals occur during a line movement of the nozzle with a switched-on electric current. The depth of a line removal depends on the dwell time over the machined workpiece surface and can be influenced by nozzle velocity and number of repetitions of the same line removal. By using complex nozzle geometries, the whole line removal geometry can be affected [7]. The line removals, as seen in Fig. 2b), were each machined with three superimposed lines [6]. Noticeable is the reproducibility and the high quality of the line removal.

A machined plane surface can be realized by an overlay of line removals, as seen in Fig. 3a). The line removals have a defined distance to each other. This defined line distance is caused through a specific motion in one direction. In order to avoid additional removal, this motion takes place without switched-on electric current. To reach a high surface quality, the kinematic roughness has to be considered. Hackert [8] shows, that the kinematic roughness is nearly steady, if the line distance is smaller than the inner diameter of the nozzle. By a rise of the line distance, the kinematic roughness increases to a maximum. The maximum is reached if the line distance has the width of 1.9-fold of the nozzle diameter [8].

Another removal movement is the contour removal, where the removal takes place along a contour path. The contour removals can be executed through a programmed trajectory with different motion commands. Contour removals are applied to machine for example channels for a microreactor. To get a constant depth for the microstructure, the nozzle velocity has to be equal for each motion commands. Fig. 3b) shows an example of a machined microstructure in form of a microreactor. The cavities are machined in stainless steel with a depth of 60 µm and a width of 200 µm [2].



a) Plane surface removal [8] b) Contour removal (microreactor) [2]

Fig. 3. SEM images of a plane surface and a microreactor generated with Jet-ECM.

Jet-ECM prototype system

The design of the Jet-ECM prototype system at the OVGU is shown in Fig. 4. The prototype system is housed in a casing to prevent reaching into the system during processing. The extraction system vacuums and filters the removal gases. A granite portal is mounted on the carrying frame. The linear stages are mounted on this granite portal, that is designed in a gantry design. The nozzle system is mounted on the z-axis and the processing chamber is mounted on the x-axis. To separate the processing area and the electrolyte system, a partition wall is implemented. The electrolyte system consists of fresh electrolyte tank, filter, pump and measurement system for electrical conductivity, electrolyte temperature and pH-value.

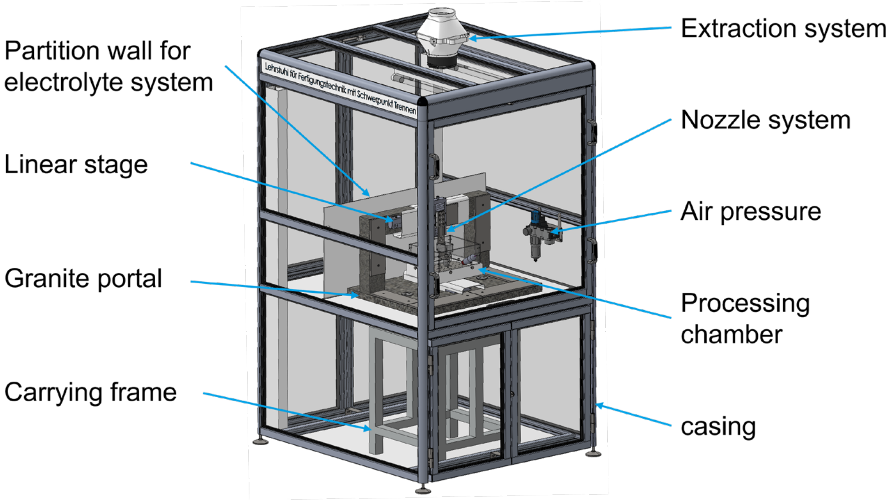


Fig. 4. Design of the Jet-ECM prototype system.

According to Fig. 5 the Jet-ECM prototype system consists of different components, that can be divided into the main parts electrolyte system, power supply, nozzle system, data acquisition, positioning system and control system.

The electrolyte system supplies the Jet-ECM prototype system with an electrolyte. A micro annular gear pump pumps the electrolyte through a filter out of an electrolyte tank. The flow rate of this micro gear pump is in range of 0.048 ml/min to 288 ml/min. The electrolyte is transported to the nozzle system and is ejected perpendicular to the workpiece surface. The used electrolyte is collected in the processing chamber. Afterwards, the electrolyte is discharged to the disposal tank.

A maximum voltage of 50 V and a maximum current of 7 A can be set with a digital laboratory power supply, which is locally and remotely programmable.

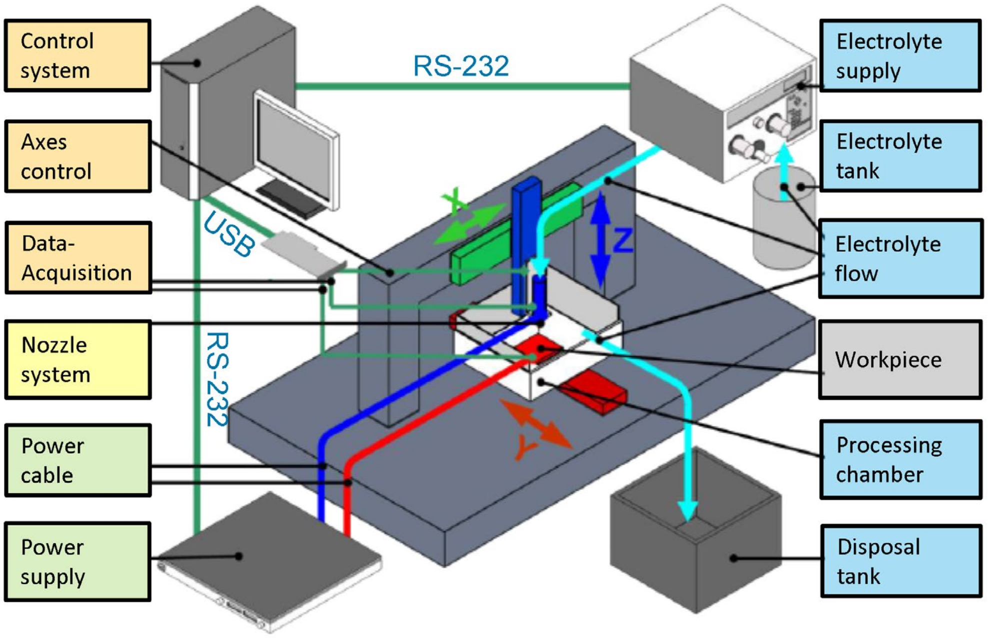


Fig. 5. Components of the Jet-ECM prototype system according to [2].

The nozzle system consists of a nozzle, nozzle holder, cathode contact and connections for the electrolyte and air pressure. The nozzle system defines the position of the nozzle to the workpiece. Furthermore, the nozzle system supplies electrolyte and electric current.

To measure analogue signals and to generate digital output signals, a data acquisition device is used. Through analogue inputs for instance the process voltage, working gap voltage and the process current are measured. The digital outputs are used to switch the process voltage and the air pressure.

The positioning system consists of three linear stages and a motion control. A motion controller is utilized to control the nozzle movement in three axes. Various motion profiles, e.g. multi-axis point-to-point, multi-axis segmented motion or third order profiles can be executed.

To control the whole machining process, a control system, called Jet-Control, was programmed based on the commercial software LabVIEW. All process operations and tasks can be controlled by using Jet-Control. To add a possibility for the user to interact with the Jet-ECM process, a user-friendly human machine interface was designed. Based on the interface, the user can observe, adjust and control the Jet-ECM process. Caused by the variety of different components and by adding new features, the GUI becomes quickly too complex and confusing. Therefore, the GUI was redesigned, using established design guidelines for machine systems.

Concept of the Human Machine Interface

To design a human machine interface, it is recommended to consider the function first and the presentation later [9]. Therefore, the user tasks have to be analysed and sorted due to their importance and their frequency. Accordingly, a task flow is analysed, that shows the sequence for machining a microstructure. As seen in Fig. 6 the task flow can be separated in three main tasks: preparation, processing and post-processing. In the preparation task, the user has to enter the motion commands of a trajectory into a process file. The user loads the process file into the software Jet-Control. Furthermore, the process parameters, for example process voltage, nozzle velocity, flow rate, etc., have to be set. To set the working gap, the user can choose an assisted program which is included in the GUI. To do this, the user manually moves the nozzle to a desired position over the workpiece and enters the required distance of the working gap. With starting of the assisted program, the nozzle is moved into the workpiece direction until an electrical contact is determined. After reaching the electrical contact with the workpiece surface, the working gap is set automatically. For this purpose, the nozzle is moved in opposite direction from the electrical contact position and positioned at the required distance from the workpiece surface.

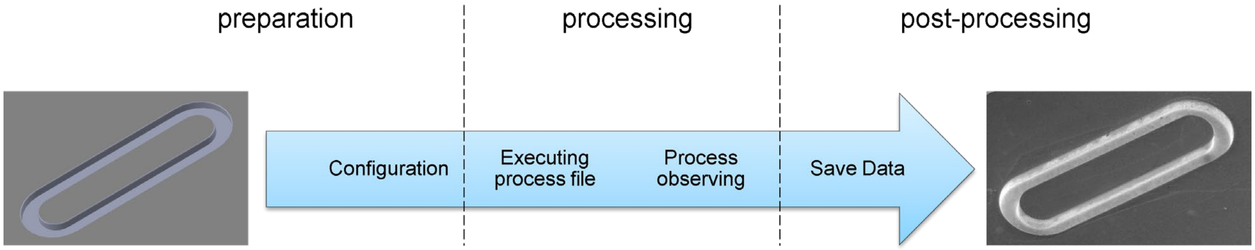


Fig. 6. Task flow to generate a microstructure with Jet-ECM from CAD to machined sample (picture on right hand side from [6]).

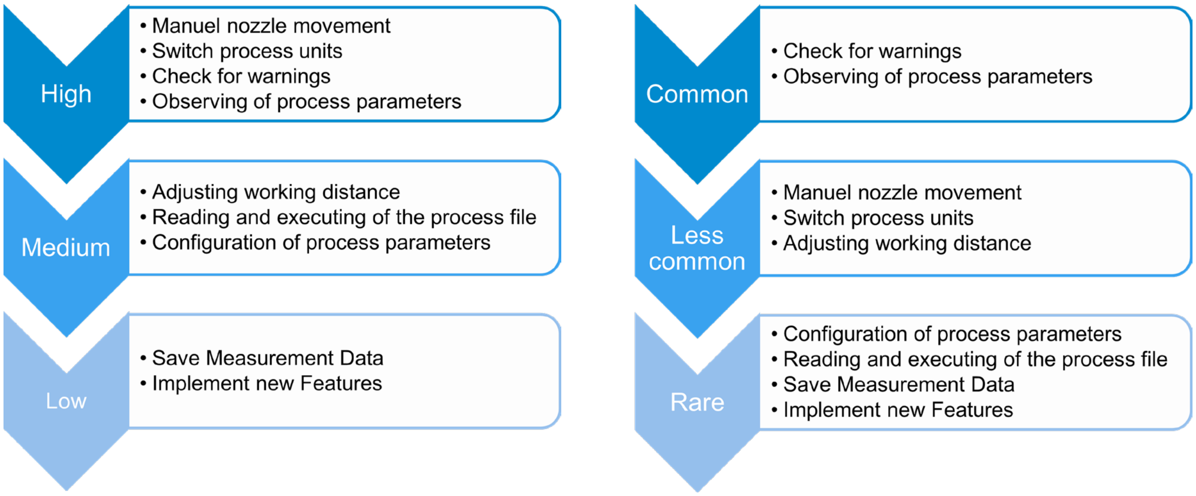
After the preparation, the processing task can be started by the user. During the processing task, the removal process takes place based on the set process parameters and the process file. The user can observe the process via GUI by checking different diagrams, LED's, text or number inserts. Furthermore, the user can interact anytime for warnings and errors.

After the removal process, the post-processing task begins. In the post-processing task, Jet-Control saves selected measurements, such as process current, nozzle position or nozzle velocity, that were recorded during the machining process. Based on the stored measurements, the current characteristics can be determined and the electric charge can be calculated.

Throughout the analyses of the task flow, the common user tasks can be derived. These tasks are listed in Fig.7 and are weighted of their importance and their frequency. Fig. 7a) shows the importance of user tasks. For the Jet-ECM process, it is necessary to switch the process units, such as power supply or electrolyte supply, check for warnings, observing the process parameters and control manually the movement of the nozzle. These functions should always be visible during the whole process.

Less important tasks are configuration or adjusting the working gap, because these tasks have to be performed once during the process. That's why, these tasks shouldn't be visible during the whole process and should be selectable than needed.

Tasks such as save data or implement new features are not required for the process or for the user. Accordingly, these tasks should play a minor role and not be focused or visible.



a) Importance of user tasks b) Frequency of user tasks

Fig. 7. List of common user tasks weighted by their importance and frequency.

Fig. 7b) shows the frequency of the user tasks, according to which the visibility should be based. Therefore, the warnings and process parameter should take up the most space. The less common user tasks, such as manual movement or switching process units, should be less visible. The rare user tasks shouldn't be visible, only visible during selecting.

To design the presentation of the GUI, a layout is being used according to Zühlke [10]. The presentation consists of a two-dimensional mask layout, which covered the whole window, as seen in Fig.8. The window is separated into single sections. Each section has its own unique function or task. The section on the top right is called status domain. This domain shows the operating mode of the prototype system. Next to the status domain are the error domain and the command domain. The error domain displays the warning and error messages. The command domain displays, which operations are currently executed. These three domains are located on the top and are always visible. On the right side, the domain of direct functions is located. This domain is used to trigger direct operation functions, that are independent of the activated mask, but dependent on the state of the prototype system. An example of an independent function is the emergency stop, which is always useable.

The domain of direct functions is also visible and operable during the whole machine process. The working domain is placed in the centre of the window. The working domain displays specific functions, which contains the main tasks and information. The navigation domain is located below the working domain. Due to the navigation domain, the user can choose specific functions, that are displayed in the working domain.

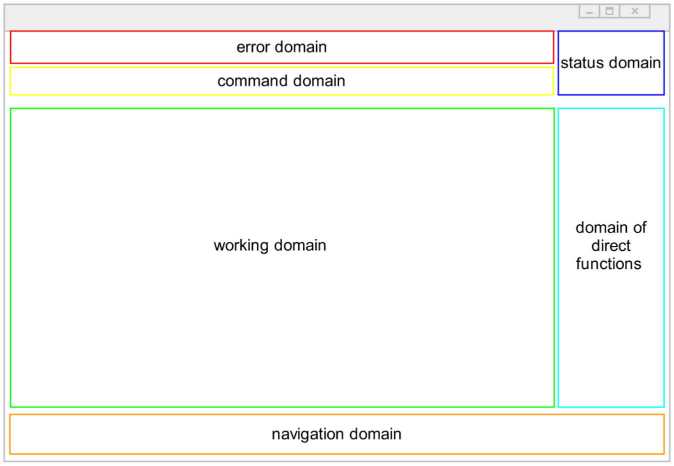


Fig. 8. Conceptional mask layout according to [10].

Based on the mask layout, the GUI was designed. The GUI consists of four different mask layouts, that can be chosen by the navigation domain. The mask layouts are differentiated by the working domain, which are: *overview*, *configuration*, *working gap* and *process file*. The mask layouts for the working domains *overview* and *configuration* are shown in Fig 9.

As described before, the error domain, command domain and status domain are placed on the top, because there is the biggest attention of the user [10]. The domain of direct functions is used for the manual movement of the nozzle, for switching the process units like power supply or electrolyte system and for the emergency stop. The emergency stop is configured to abort the removal process at any time as quickly as possible. When pressed, movements are stopped immediately and all process units, e.g. power supply and electrolyte system, are switched off.

The navigation domain consists of different buttons. Four of these buttons are actually assigned with domains and two of them can be used to add new functionality. The *EXIT* Button on the right is used to end Jet-Control. As seen in Fig. 9a), the working domain *overview* is selected. The overview displays all the important information and measurements in tabular form. In addition, process parameters are visualized in various diagrams that the user can select. Fig. 9b) shows the working domain *configuration*. At the configuration, the user can select different parameter to adjust the processing units. Furthermore, the user has the possibility, to save new process parameters via a save button for each system. To undo the change, the user can click on the default button.

At the mask layout for the working domain working gap, as seen in Fig. 10a), the user can operate the function to adjust the working gap. Firstly, the user starts to select a strategy and set a distance for the working gap. Under the dropdown field, the user can activate the process. Due to the domain of direct functions, the user can move the nozzle to a position, there the user wants to set the defined working gap. After clicking the button *approach contact*, the touching process begins. Through diagrams and LED's, the user can observe the process. The user could cancel the process anytime. After setting the working gap, each touched position will be display in tabular form for the x, y and z position and could be used for the following removal process.

a) Overview-mask: Compilation of process parameters in tabular and diagram form

b) Configuration-mask: Setting of process variables

Fig. 9. Mask layouts for the working domains: overview and configuration.

Fig. 10b) shows the mask layout for the working domain *process file*. This working domain is needed to load and execute a process file. The process file contains movement commands and switching commands for the removal process. In the dropdown field, the user chooses the desired process file and load the file over the button *load process file*. Afterwards, the file displayed at the window on the left side. Due to the radio buttons, the user can select different file types for saving the measurement data and can adjust the sampling rate. With clicking on the button *start process file*, the machining process will start and can be stopped with *CANCEL* or the *emergency stop*.

a) Working gap-mask: Program-assisted setting of the working gap

b) Process file-mask: Visualisation and executing of commands for machining

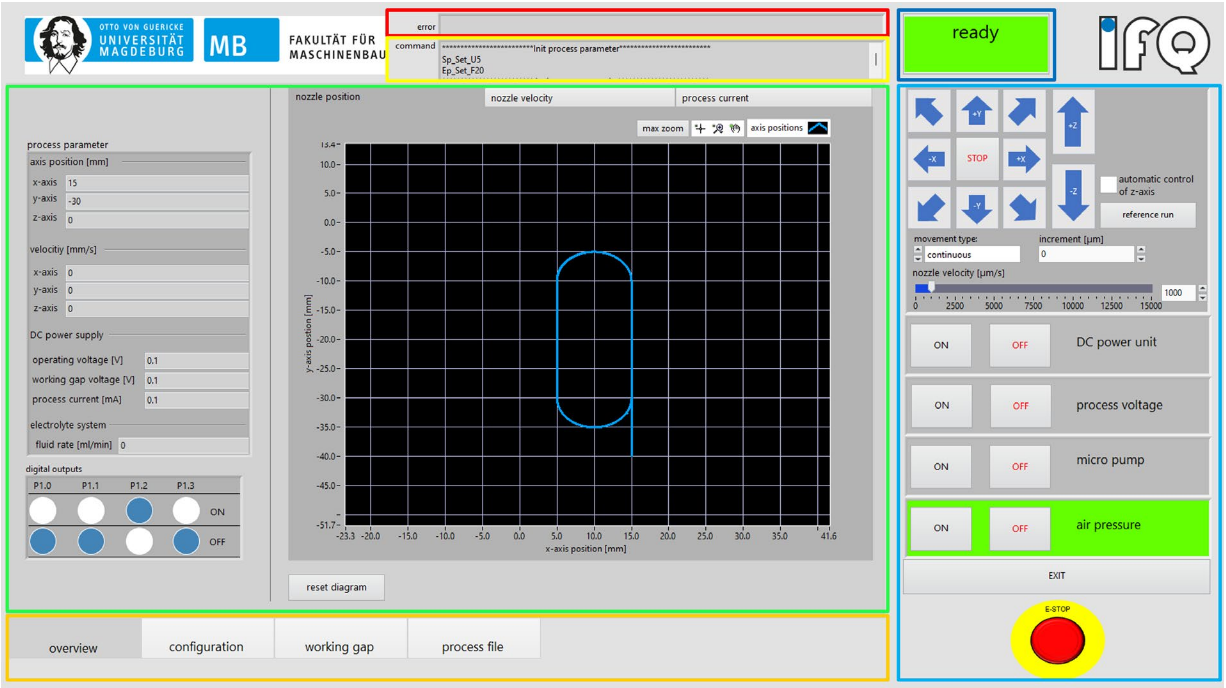
Fig. 10. Mask layouts for the working domains: working gap and process file.

Designed User-Friendly Human Machine Interface

Based on the GUI concept, a human machine interface was designed and implemented with LabVIEW, as seen in Fig. 11. To ensure user-friendliness, the mask layouts are kept minimalist, that each mask only contains the information, that the user needs. Furthermore, identical information is placed at the same location. Operating elements are arranged according to the material, energy and information flow. In Fig. 11 the different sections are framed in colour for a purpose of presentation. For example, the error domain is framed in red and the command domain is framed in yellow. Due to the importance of these domains, they are additionally placed at the top. Through text inserts, the GUI displays error messages in the error domain and displays executing tasks in the command domain. The status domain consists of an Enum-ring, which contains the status messages: initialization, ready, running and error. These messages represent the status of the machining process and are presented accordingly in text and colour. Green for the status initialization and ready, flashing green for the status running and red for the status error.

On the right side, the domain of direct functions is placed and is framed in light blue. In order to highlight the actors of the process unit, the actors are grouped into clusters. The first cluster contains arrow keys to manually move the nozzle. Furthermore, in the cluster are different buttons located, to set the type of movement, velocity and increment. By clicking the checkbox *automatic control of z-axis,* the readjustment movement of the *z*-axis can be activated or deactivated. The following clusters contain the process units, that can be controlled by *ON* and *OFF* buttons. To highlight the switching state, the background colour of the cluster changes to green when a process unit is activated.

The navigation domain is framed in orange and is realized using a tab control. Each tab activates a different working domain, which is framed in green. With adding new tabs, new features or functions can be implemented to the GUI.



error

command ************************Init process parameter************************
Sp_Set_U5
Ep_Set_F20

ready

process parameter

axis position [mm]
x-axis 15
y-axis -30
z-axis 0

velocitiy [mm/s]
x-axis 0
y-axis 0
z-axis 0

DC power supply
operating voltage [V] 0.1
working gap voltage [V] 0.1
process current [mA] 0.1

electrolyte system
fluid rate [ml/min] 0

digital outputs

P1.0	P1.1	P1.2	P1.3	
○	○	●	○	ON
●	●	○	●	OFF

☐ automatic control of z-axis

movement type: continuous
increment [µm] 0
nozzle velocity [µm/s] 1000

Fig. 11. *Implemented GUI concept in LabVIEW with outlined section.*

As seen in Fig. 11 the working domain *overview* is selected. On the left side, all process parameters grouped into a cluster. At the bottom, a table is located, which displays the state of the digital outputs. On the right side, a tab control is placed, from which the user can select which diagram to activate.

Summary

The study focused on a design of a user-friendly human machine interface for jet electrochemical machining. Through the developed interface, the Jet-ECM process can be controlled as well as user tasks can be assisted, for example for the working gap setting. Caused by the variety of different components and by adding new features, the GUI becomes quickly too complex and too confusing. Therefore, established guidelines were applied to design a human machine interface for the Jet-ECM process. To ensure a user-friendly interface, the interface was designed minimalistic and the operating elements were arranged according to the material, energy and information flow. To determine the order and the visibility of user tasks, a task flow of the Jet-ECM process was analysed. Therefore, the frequency and the importance of the user tasks were worked out. The GUI was designed based on a two-dimensional mask layout. The interface can be extended for later functions or features by adding new mask layouts.

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