

# DESIGN OF CNC MILLING MACHINE AS A BASE OF INDUSTRY 4.0 ENTERPRISE

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This article deals with a designing of one part of a smart factory model with the Industry 4.0 principles. It is a three-axis CNC milling machine with automated changes of tools and workpieces. The emerging factory is not controlled centrally, but each facility has its own control system and communicates with other facilities via IoT – Internet of Things principle.

The machine tool is designed to machine easily machinable materials such as artificial wood, plastic and aluminium alloys. The milling machine will also be used as an education aid. It will be used for manufacturing demonstration as well as for demonstration of basic construction elements of a CNC milling machine.

## KEYWORDS

CNC milling machine, smart factory, Industry 4.0, GRBL, Arduino

## 1 INTRODUCTION

The term 'Industry 4.0' refers to a fourth industrial revolution based on using the Internet of Things concept, cyber-physical systems and other modern technologies, which are to bring full digital interconnection of all manufacturing processes (from development to distribution of the product). [ATP 2016, Kaminsky 2016]

It will allow complete digital interconnection of the entire production system, including machines, leading to a 'smart factory' of the future. Various equipment would implement computer chips capable of wireless Internet communication with each other. Manufacturing would take place in autonomous manufacturing systems, where all parts of the system, including the products themselves, would communicate with each other and form a so called cyber-physical system. [Manlig 2016, Prima 2016]

Concepts of technology: [Musil 2016]

- Cyber-physical systems (CPS) as the fundamental part of automation of manufacturing processes.
- Internet of Things (IoT) uses wireless technology to allow sharing and transmission of data between systems as well as control and supervision of these systems.
- Internet of Services (IoS) and Digital Economy. IoS offers services provided inside an enterprise allowing using cloud storage for on-line business transactions.
- 'Big Data & Clouds' allow processing and collection of large data sets.

Concepts of informatics: [EZU 2016]

- Interoperability is a possibility to communicate through IoT and IoS.
- Virtualization is an ability to create a virtual model of a factory using data received from machines' sensors.

- Decentralization is an ability of a machine to organize and control a process, leading to optimization of manufacturing.
- Real-time work allows unlimited communication for system control.
- Orientation to both offered and used services.
- Modularity is a system ability to react to change of situation.
- Convergence and interconnection of technology – interconnection of data and telecommunication networks and data centres.

## 1.1 Smart factory model

Purchase or construct of individual components is required for the created smart factory model. There will be products that can be uniquely identified by means of chips. Their history, current state of the product and where it is located will be known. Each product will be mapped from the start of production until the final stage. From the perspective of Industry 4.0, this will be a manufacturing process and industrial equipment control by means of control systems. However, people will be the decisive element, who will never be fully replaced by machines, and will work in positions where they can utilize their experience and their thinking and planning abilities. [Simeonova 2016]

A three-axis CNC milling machine will be a fundamental part of the created concept. The main goal for verification, production and optimization of communication algorithms in the created smart factory model is not to use large production milling machines. Using small models with far lower prices is more suitable. If the system design and control is open, it will be far simpler to adapt the system to individual needs. Particularly, this relates to communication with surrounding manufacturing system components, but machine hardware modifications are assumed as well, e.g. implementation of automated clamping of a workpiece.

Basic prerequisites and requirements for a CNC milling machine:

- Basic parameters of the milling machine according to a table (Tab. 2).
- As low weight as possible (for easy handling).
- Tool magazine for automated change.
- Open-source control software for possible modification.
- Fitting with sensors for control of machine state, manufacturing process and remote operation.

## 2 MARKET ANALYSIS OF SMALL CNC MILLING MACHINES

As mentioned above, a CNC milling machines will be a fundamental mean of production of the designed smart factory model. This chapter contains a research of small CNC milling machines by various manufacturers currently available at the market. These are mostly educational or hobby machines intended for milling non-ferrous materials such as plastic, wood and aluminium alloys.

Basic specifications of these machines are summarized in Tab. 1, examples are shown in Fig. 1, 2, 3.



Figure 1. MC30FT milling machine [Merkur 2018]

As seen in the table, available milling machines have a disadvantage mainly in small range of Z-axis motion. Since no milling machine with tool magazine for automated tool change was found, the axis range is insufficient for implementing an automated tool change feature into the existing small machine. Furthermore, most available milling machines offer relatively small spindle power – around 100 – 200 W, which is suitable for engraving, but limiting for milling using a cylindrical mill with e.g. 8 mm diameter.



Figure 2. Hobby CNC milling machine [ABE.TEC 2018]

Axes dimensions influencing the work-piece size and table size determining the possibility of mounting a clamp and the size of workpiece are important parameters as well.

Since no machine tool with suitable parameters was found, own product meeting the basic parameters listed in Tab. 2 has been designed. The designed milling machine will thus seek to combine the benefits of the researched milling machines to achieve the desired working space size and accuracy.



Figure 3. 3040 Z-DQ 3D CNC milling machine [CNCworld 2018]

### 2.1 Research findings

Milling machines can be defined by various parameters, which is why the selection of the most suitable milling machine is not so clear. There are many circumstances – purpose of the machine, what will be milled, what does buyer expect (accuracy) and price of the machine.

Specifications of milling machines	MC30FT [Merkur 2018]	30x40 CNC [KB 2019]	GV 21 2A [Gravos 2019]	Hobby CNC [ABE.TEC 2018]	3040 Z-DQ 3D [CNCworld 2018]
Working table dimensions [mm]	330 x 300	300 x 400	390 x 390	320 x 420	320 x 530
Rapid traverse [mm/min]	N. A.	4,000	3,930	N. A.	4,000
Motion range – X-axis [mm]	180	280	215	295	300
Motion range – Y-axis [mm]	210	390	165	195	400
Motion range – Z-axis [mm]	90	55	65	70	75
Space under Z-axis portal [mm]	110	70	100	80	75
Spindle power [W]	100	300	175	without spindle	500
Spindle speed [rev./min]	5,000 – 20,000	1,200	5,000 – 35,000	-	300 – 11,000
Control system	ARMOTE	MACH3	ARMOTE	Linux CNC	MACH3
Weight [kg]:	21	28	17	9	28
Tool magazine	no	no	no	no	no
Price, VAT included [CZK]	36,500	N. A.	69,000	16,249	25,299

Table 1. Specifications of milling machines

### 3 DESIGN OF CNC MILLING MACHINE

Design of the milling machine will correspond to its intended use. This machine tool will be used for machining easily machinable materials such as artificial wood, plastic and aluminium alloys. The design will be based on the minimum work area dimensions, which are 200 x 200 x 150 mm. Additionally, the design must be a trade-off between sufficient stiffness of the mill and the lowest possible weight, allowing handling with the machine, as it will also be used for educational purposes.

When designing the milling machine, it is also important to try to use as many components available on the market as possible, so that it is not necessary to produce large numbers of individual parts. The basic structure will consist of aluminium profiles, other structural part will be primarily made of aluminium plates.

The profile guideways with bearing packs will be used for axes X and Y, where the rail is fixed to machine frame. Z axis uses cylindrical guide rods with linear bearings with 16 mm diameter. This is due to cost effectiveness, since the load is not so high in this case. Drives are dimensioned for ball screws with 12 mm diameter and screw pitch 4 mm with pre-tensioned nut.

Specifications	Parameters
Motion range – X-axis [mm]	250
Motion range – Y-axis [mm]	260
Motion range – Z-axis [mm]	150
Rapid traverse [mm/min]	2,000
Maximum diameter of mill [mm]	8
Table dimensions [mm]	320 x 460
Machine accuracy [mm]	0.1
Tool magazine, capacity	yes, 5 tools

Table 2. Proposed parameters for milling machine design

#### 3.1 Selecting spindle and drive

This chapter contains calculations used for selection of spindle and drive of motion axes with respect to mill requirements.

##### 3.1.1 Calculation of machining forces

Calculations will be made for maximum assumed load of the machine. With respect to ER16 clamp, the largest diameter of milling tool is assumed to be 8 mm. Recommended cutting conditions for machines milling aluminium alloys with silicon content ( $Si \leq 0.45$ ) are determined by means of Pramet catalogue [Pramet 2012]. Calculations are made using literature [Marek 2015, Mendricky 2008].

Required spindle output when milling

$$P = \frac{a_p a_e v_f k_c}{60 \cdot 10^3} = \frac{28730 \cdot 1320}{60 \cdot 10^3} \doteq 257 \text{ [W]} \quad (1)$$

Cutting force when milling applied onto each tooth currently in force

$$F_c = k_c \cdot a_p \cdot f_t = 1320 \cdot 2 \cdot 0.08 \doteq 211 \text{ [N]} \quad (2)$$

Torque applied on tooth when milling

$$M_k = F_c \cdot \frac{D}{2 \cdot 10^3} = 211 \cdot \frac{8}{2 \cdot 10^3} \doteq 0.85 \text{ [Nm]} \quad (3)$$

##### 3.1.2 Selecting spindle

Selection of spindle was based on calculated values, required spindle output, cutting force and torque applied on tooth when milling. Here, there was a problem with market availability of suitable small spindle. Due to the requirement of automated tool change feature, production of own spindle design has been decided. The spindle would use a DC drive with 400 W output and PWM controller with speed regulation between 3,000 and 12,000 revs per minute. The own spindle is connected to the drive by means of belt transmission with 1:2 gear ratio. Adapter with ISO 20 coupling on the machine-side is used as tool holder. Spindle structure design, including control of ISO 20 adapter clamping control during cutting process is shown in Fig. 4.

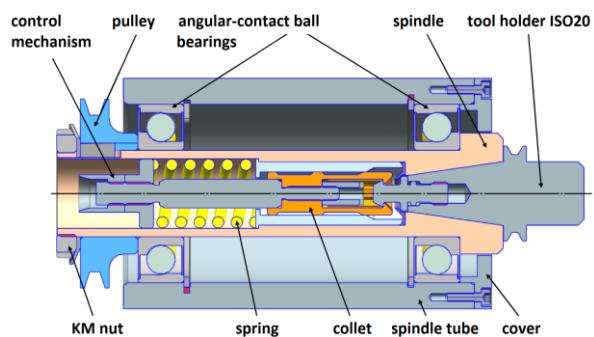


Figure 4. Structure of designed spindle

#### 3.2 Selection of stepper motors

Linear motion on X-axis as well as on Y- and Z-axis is secured with ball screws with pre-tensioned nut.

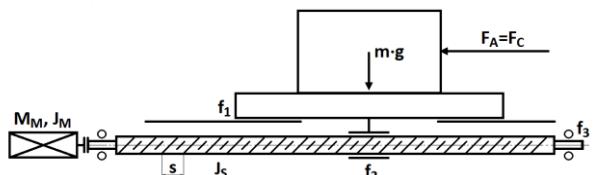


Figure 5. Calculation model of the machine axis

Calculations of required torque for selection of stepper motors have been made using literature [Marek 2015]. A generally available ball screw with 12 mm diameter and 4 mm pitch has been selected. The screw is bilaterally seated in ball bearings. The screws are fixed on one end with radial and axial force absorption. The other screw end is supported absorbs radial forces only. In the calculations below,  $F_a$  axial force shown in Fig. 5 is assumed as  $F_c$  maximum cutting force is calculated from conditions provided in equation (2).

The required torque is calculated from static and dynamic points of view, i.e. from equations (4) and (9).

##### 3.2.1 Static point of view

First, it is necessary to calculate the torque according to the static point of view:

$$M_S = \frac{F_A \cdot S}{2 \cdot \pi} + M_{zsrbm} \quad (4)$$

In this case, load torque reduced to drive shaft  $M_{zsrbm}$  consists of the following components:

- Load torque applied by frictional forces of moved masses:

$$M_G = \frac{m \cdot g \cdot f_1 \cdot s}{2 \cdot \pi \cdot \eta_s \cdot \eta_L^j} = \frac{12 \cdot 9.81 \cdot 0.005 \cdot 0.004}{2 \cdot \pi \cdot 0.92 \cdot 0.97} \doteq 4.2 \cdot 10^{-4} [\text{Nm}] \quad (5)$$

- Load torque applied by frictional forces in bearing:

$$M_L = 0.5 \cdot (F_A + m \cdot g \cdot f_1) \cdot d_L \cdot f_3 \quad (6)$$

$$M_L = 0.5 \cdot (211 + 12 \cdot 9.81 \cdot 0.005) \cdot 0.007 \cdot 0.003$$

$$M_L \doteq 2.2 \cdot 10^{-3} [\text{Nm}]$$

- Torque applied by frictional forces between the nut and motion screw:

$$M_{KSM} = \frac{(F_A + m \cdot g \cdot f_1) \cdot d_S \cdot f_2}{2 \cdot \eta_L^j} \quad (7)$$

$$M_{KSM} = \frac{(211 + 12 \cdot 9.81 \cdot 0.005) \cdot 0.011 \cdot 0.003}{2 \cdot 0.97} \doteq 3.6 \cdot 10^{-3} [\text{Nm}]$$

- Static torque:

$$M_S = \frac{211 \cdot 0.004}{2 \cdot \pi} + 4.2 \cdot 10^{-4} + 2.2 \cdot 10^{-3} + 3.6 \cdot 10^{-3}$$

$$M_S = 0.140 [\text{Nm}]$$

### 3.2.2 Dynamic point of view

Next, it is necessary to calculate the reduced moment of inertia applied onto the drive shaft, see equation (8). The calculation will be made for X-axis with the highest load.

$$J_{RED} = m \cdot \left(\frac{s}{2 \cdot \pi}\right)^2 + J_S + J_M \quad (8)$$

$$J_{RED} = 12 \cdot \left(\frac{0.004}{2 \cdot \pi}\right)^2 + 5.8 \cdot 10^{-6} + 8.2 \cdot 10^{-6}$$

$$J_{RED} \doteq 1.9 \cdot 10^{-5} [\text{kg} \cdot \text{m}^2]$$

Dynamic torque for motion of masses on X-axis:

$$M_D = J_{RED} \cdot \varepsilon = 1.9 \cdot 10^{-5} \cdot 800 \doteq 0.015 [\text{Nm}] \quad (9)$$

Total torque to be overcome by the proposed stepper motor during maximum load is therefore a sum of static and dynamic torque, see equation (10).

$$M = M_S + M_D = 0.140 + 0.015 = 0.155 [\text{Nm}] \quad (10)$$

### 3.2.3 Selection of stepper motor

Based on the calculated values and drive torque for motion of ball bearings, SX17-1005 motor has been selected, see Fig. 6. Nominal torque of this motor is 0.52 Nm while its nominal current is 1 A. Nominal torque of the motor is higher in order to secure sufficient torque even during load, see torque characteristics in Fig. 7.

These motors will be used on all three motion axes, for control of the tool clamp to the spindle for securing automated change of tool and for control of toll magazine parallelogram.



Figure 6. SX17-1005 stepper motor [Microcon 2017]

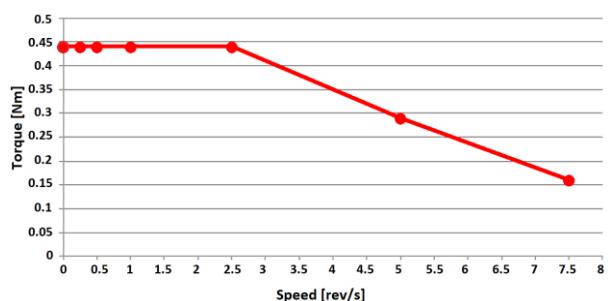


Figure 7. SX17-1005 motor torque characteristics [Microcon 2017]

### 3.3 Tool magazine

Initially, the tool magazine has been designed with fixed number of five slots. This means that there is a bar in the machine's working area, to which the spindle moves during replacement. If there is a tool in the spindle, the tool is approached horizontally and after the unclamping is released, the spindle moves vertically upwards. When clamping the tool, the procedure is reversed - the spindle moves over the tool and moves down to clamp it. The spindle then moves away from the magazine horizontally.

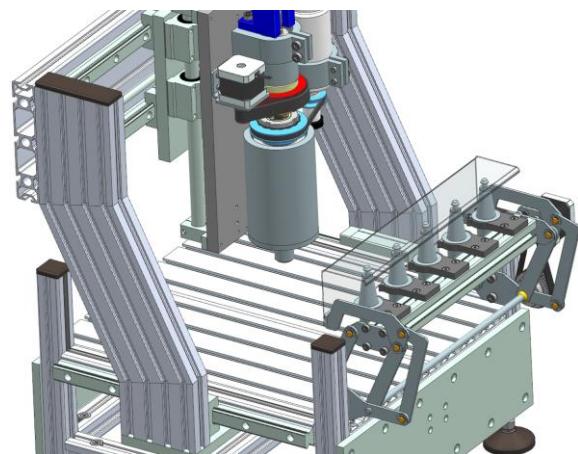


Figure 8. CNC milling machine with embedded tool magazine

Since this concept takes quite a lot of workspace, displacement of magazine for unused tools outside the mill work area has been designed by means of parallelogram controlled by another stepper motor. Tool magazine design is shown in Fig. 8.

#### 4 CONTROL SYSTEM DESIGN

Control system is an integral part of a CNC machine. It is therefore important for it to allow control of all functions, features and peripherals of the designed machine. Standard commercial control systems used with large production machines were excluded for price reasons. Therefore, so called hobby systems were extensively analysed as these systems are used with similar CNC machines.

In this case, an important requirement for the control system is its openness, ideally with available source code allowing later modifications. This is important particularly for the requirement of automated tool change, since this feature basically does not exist in these systems and it is therefore necessary to program it.

Systems used by similar machine segment are the following in particular:

- MACH3 [Fenerty 2006]
- Linux CNC [LinuxCNC 2019]
- ARMOTE, or similar communication control system by Gravos [Gravos 2019]
- GRBL and its clones [Jeon 2011]

MACH3 is a PC-based control system by ArtSoft. Machine control is allowed through parallel PC port connected to power components for drive and spindle control. The program runs on computers with Windows OS. However, this is not an open-source program. [Fenerty 2006]

LinuxCNC is also a control system intended for CNC machine control directly from a PC through power separation of actuators. It runs on Linux-based operation systems (Debian, Ubuntu, etc.) and is available for free, including source codes. It features control of both, stepper motors and servomotors. [LinuxCNC 2019]

Some hobby milling machines available at our market uses Armote software for Windows. In this case, the control system consists of two basic parts and power components. User interface runs on a computer communicating with interpolation unit, which handles communication and control of the machine in real time. An advantage of this design is that short-term interruption of communication with the computer does not affect the unit whatsoever and the milling continues without interruption. This positively affects the quality of manufacturing and tool life. However, this is not an open-source program, although the interpolation unit can be purchased separately and the PC communication protocol is very well documented. [Gravos 2019]

GRBL G-code interpreter works similarly as the previous system, i.e. the computer runs an operating software communicating with the operator and transmitting individual commands to the G-code interpreter. The interpreter then processes the received commands in real time and provides feedback to the operating software. [Jeon 2011]

So the advantages are the same as in the previous case and both the operation computer software and GRBL firmware for Arduino platform are available as open source and can therefore be modified as needed.

With regard to the said advantages of GRBL interpreter and authors' experience with programming especially for the Windows OS, it has been decided to select the Arduino system with GRBL firmware and own operation computer software for controlling the designed milling machine.

#### 5 CONCLUSIONS

The goal was to design a small CNC milling machine suitable for creating a smart factory model and for use as educational aid. The requirement was to design a machine for milling easy-to-mill materials such as artificial wood, plastic or aluminium with a clamping feature and with 200 x 200 mm dimensions and Z-axis motion range of 150 mm, allowing, besides other, automated change of tools. Portal milling machine has been selected as a small CNC milling machine for the smart factory model.

A research of small CNC milling machines available in the market has been done. The research lead to a conclusion that none of the available systems are suitable for the determined requirements and modifications of those designs would have been too difficult. Therefore, an own design has been created, which was based on the determined requirements, particularly the size of work area and automated tool change feature, and future automated work-piece change feature.

Basic calculations based on maximum machine load were made to allow selecting a suitable work tool (spindle) and selecting drive for individual linear movement axes of the machine. In accordance with these calculations, the structural design of the milling machine has been made. Firstly, the machine frame and work table have been designed, followed by design of guides and arrangement of drives for each linear motion axis of the machine. Several portal designs were made. Their advantages and disadvantages were assessed and the optimal variant has been selected.

The milling machine is made mainly of aluminium profiles and flat aluminium plates. X- and Y-axis guide is secured by prismatic guides, Z-axis guide is secured by unsupported guide rods. The system is driven by stepper motors and rolled ball screws with pre-tensioned nuts. Arduino Mega 2560 with modified GRBL firmware with PC user interface was chosen as the control unit of this milling machine. Currently, programs for controlling the spindle and stepper motors of X-, Y- and Z-axis are created and tested. In order to control clamping of the tool into spindle and own work with the tool magazine, it will be necessary to make further adjustments to the Arduino firmware as well as to the PC software.

Price of all components required to assemble the mill ranges around CZK 40,000.

After other smart factory model components are manufactured, this milling machine will be included to this model and the PC control software will be adapted to allow communication with other peripherals using the IoT principle.

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