ROBOTIC ARM DESIGN, DEVELOPMENT AND CONTROL FOR PRINTING CEMENT MIXTURES

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New innovative approaches for building construction are being developed around the world. One of these is printing cement mixtures for which various machines are now being developed. This paper deals with the design of an experimental robotic arm for research into cement mixture printing. A generative design approach was used and discussed in its development. The results describe the solutions obtained using the generative design process together with the approach used to control the drives of the robotic arm. Finally, the benefits of using generative design in solving such a large and complex task are discussed based on our experience from this particular project.

KEYWORDS

robotic arm design, robot design, generative design, printing cement mixtures, concrete printing, 3D printing

1 INTRODUCTION

Building construction is considered to be quite conservative in its use of new progressive technologies. Current construction approaches are still based on relatively old practices and the adoption of new approaches and technologies, in practice, always takes longer in this sector than in other industries. Research organizations, construction companies and technology startups around the world are pursuing innovative approaches to building which, if adopted and deployed on a wide scale, would bring significant benefits to this conservative industry. Research and development has focused on developing approaches using specialist, newly developed, equipment which would be able to replace, or reduce, the human workforce on a construction site. The aim is also to provide solutions capable of bringing a variety of architectural, structural and functional options to the field of building construction.

It is now possible to find various equipment designs being developed in different parts of the world which would bring these stated benefits into practice. These machines can be divided into machines used for the handling and precise laying of building bricks and other block materials, corresponding to the usual house building by manpower. For example, the FBR project [FBR Ltd 2021] deals with this type of technology. The second group of equipment is designed for the precision casting, or we can say printing, of liquid building mixtures, mainly cement mixtures. Based on our survey, we can state that cement mixture printing devices are being developed primarily in the form of either cartesian robots, for example the BetAbram project [BetAbram 2021], or robotic arms in various design configurations. In some cases, solutions in the form of robotic arms choose the straightforward and relatively quick option of using standard industrial robotic arms. For example, Bauminator [Baumit 2021], CON3D [Prodintec 2021] and Scoolpt [Scoolpt 2021]. Other projects, such as Apis Cor [Apis Cor 2021], and Constructions-3D [Constructions-3D 2021], take a more challenging path, involving the design, manufacture and optimisation of highly specialized robotic machines for printing cement mixtures.

Our team set out to find a comprehensive solution for building construction using printing cement mixtures. Part of our solution involves the development of printing equipment and cement mixtures. Our original approach to the design solution of the printing robotic arm was described in detail in publication [Zada 2022]. This design solution uses a SCARA structure with an added rotational axis.

The challenging assignment was therefore to create a 2.8 m long robotic arm capable of manipulating the load located at the end of the arm up to a maximum weight of 35 kg, allowing the experimental development of printing cement mixtures. Combining this with the relatively high dynamic requirements of the expected inhospitable operating conditions, such parameters can be considered to be very demanding for robotic arm design.

As this is a completely new application for such an arm, it was not entirely clear which design solution to choose. At the beginning of the design process, we asked which design method would be adequate for such an assignment? From our previous work, and literature research, we considered using the generative design process. However, we also asked if the use of generative design really was the appropriate solution for such a large and complex assignment.

This design aimed to build an experimental robotic arm which would allow the printing of objects from cement mixtures. This robotic arm is an intermediate step, on a scale of 1:2, in developing a robotic arm for printing buildings from cement mixtures with a final arm length of 5.6 m. We used knowledge gained from the design of the first robotic arm with the same structure, but on a scale of 1:4, of the final arm. The detailed side layout of the experimental robotic arm, including the dimensions of individual segments, is shown in Fig. 1.

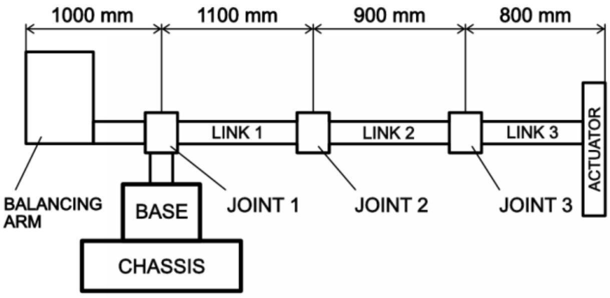

Figure 1. Robotic arm side layout on a scale of 1:2

The experimental robotic arm consists of three segments, a balancing arm, an actuator and a robot chassis. Based on the requirements for both the length of individual links and the relatively low final weight of the robot, we decided to design individual segments of the robotic arm using generative design algorithms described in the following chapter. This technical solution allowed us to design a sufficiently rigid arm with a relatively low weight. The segments of the robotic arm are connected in individual joints by rotary actuators, giving the robotic arm high force and outstanding positioning accuracy. The balancing arm was designed as a combination of steel weldment and aluminum workpieces. Electrical switchboards and steel weights are located at the end of this arm. Together these form a counterweight, which ensures stability for the robotic arm. At the end of the robotic arm is an actuator allowing a fine vertical displacement of the endpoint by 1000 mm. The base consists of a steel cylinder, allowing the attachment of the robot to the chassis. The rotary actuator in joint 1 connects the base to link 1. The base with the robotic arm is placed on a chassis welded from solid steel parts, which ensures the robotic arm is sufficiently stable. The chassis is placed on four lifting columns, enabling the device to be lifted up to a height of 2500 mm.

All the motors from Joint 1 to Joint 3 are permanent magnet synchronous motors assembled with harmonic gearboxes. This concept has the best volume to power/torque ratio. Furthermore, backlash is minimal. This allows a very precise positioning of the endpoint (a printing head). These motors are equipped with absolute encoders to determine the position of all Joints without homing procedure. Other actuators are equipped with standard planetary gearboxes. All motors are driven by the servo controller ACOPOS P3. Their motion can be synchronized via real-time bus POWERLINK with a 400 us period. This is important for path-controlled movement.

2 METHODS

2.1 *Robotic arm design*

The design of the robotic arm is based on an innovative process called Generative Design, something which has become increasingly popular recently in the area of technological development, thanks to increasing computing power and the advent of artificial intelligence. Generative design is an approach in which the designer and the computer come together as co–creators. The algorithm mimics the natural evolutionary approach and quickly explores thousands of design proposals. With the ability to learn from each iteration, and the ability to apply change at each stage of the design, it creates an optimized solution that meets all predefined parameters (e.g., load, material, rigidity, target mass or material). The result is a lightweight design with an organic look that would not otherwise be possible using traditional design processes, something which is ideal for additive production, among other things. It's undeniable advantage is that this design process significantly speeds up time–to–market procedures [McKnight 2017]. Generative design tools are already being routinely used by several companies, notably in the automotive and aviation sectors. General Motors started using this technology in 2018 to design a new seat holder, making it 40 % lighter and 20 % stiffer than the previous version [Ntintakis 2020]. Generative design thus becomes another important tool in addition to the already commonly used topological optimization. Topological optimization can already be considered a proven approach in mechanical enginnering with a wide user base [Pastor 2021].

The components designed in this project using generative design were the three links of the robotic arm connected by motors within individual joints. The primary mechanical design process followed; the workflow is shown in Fig. 2. Based on the endpoint requirements, together with the required robot layout described in the introduction of the paper, we analyzed different possible arm positions that cause different loads on the individual links. The positions of the robotic arm causing significant loads on each link are shown in Fig. 3.

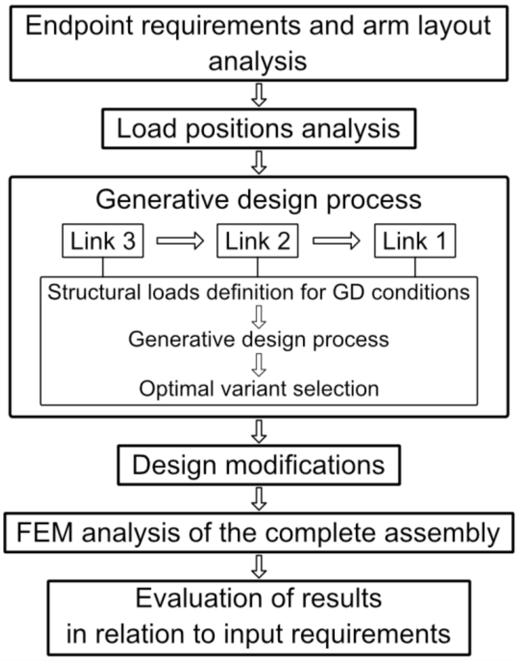

Figure 2. Robotic arm mechanical design process

This analysis provided us with the required loads for each link. These loads were then used to define the structural load conditions of the generative design. We proceeded sequentially from link 3 through link 2 to link 1. We always defined the structural loads of the generative design conditions for each link. Subsequently, we conducted the generative design process, which provided us with different possible results depending on the global displacement of the link endpoint and its mass. We selected the optimum variant of the final shape of each link based on acceptable values of the global displacement and safety factor. We chose final shapes that achieved a safety factor higher than 2.5. We believe that a higher safety factor can account for possible dynamic loads. Due to the planned use of cement mixture printing technology, there was no need to consider the loads from this technology. Based on our previous experience with the development of this technology, it can be concluded that this technology does not produce significant loads at the point of placement, as it only involves fine control of the extruding liquid cement mixture in the direction of the vertical axis. The selection of the optimum variant of the individual links, together with the design modifications to the links and the follow-up FEM analysis of the complete assembly, is continued in more detail in Section 3.1.

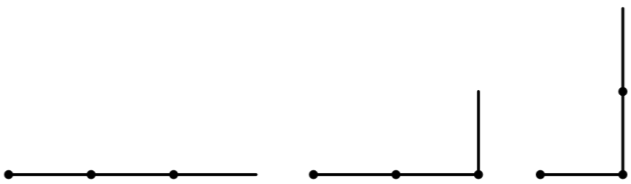

Figure 3. Robotic arm positions causing significant loads on each link

In addition to the dimensional parameters shown in Fig. 1, the maximum endpoint displacement at maximum load was also considered in the design. The specific endpoint requirements are listed in Tab. 1.

Max. load	35 kg
Max. displacement	3 mm
Max. speed	0.5 m/s

Table 1. Robotic arm endpoint requirements

The process of designing individual segments of the robotic arm will not be described in detail here. We will focus, instead, on the last segment of the robotic arm. The design process for the other segments was identical. The input geometric requirements for generating the design are shown in Fig. 4. The image shows the parts catagorised by different colours. In red, there are parts that must remain intact and unaltered by the algorithm during design. In this case, it is the sliding member, motor and the place for bolt locations. The components determining the starting points for algorithm connection are in green. The force effect of the gravitational force is shown in yellow. The structural load forces are shown in blue. The fixed structural constraint is defined on the motor flange.

The design goal is to reduce the weight of the component while maintaining sufficient ridigity from the aluminum alloy EN–AW 5083 (AlMg4,5Mn0,7). Manufacturing technology for this design has been selected as 5–axis milling, as this technology is the most accessible to us.

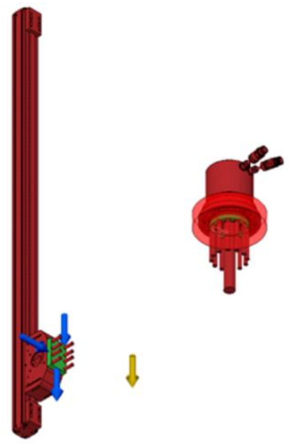

Figure 4. Input geometric parameters in design of segment 3

The robotic arm is equipped with seven electric drives. Four mechanically independent drives M1 – M4 are intended as a lift for the robot base, changing the height of the printed layer. One serves as the actuator for changing the position of the printing head at the end of the robotic arm marked Z. The last standard axis is E for extruding cement mixture from the printing head. All these drives are produced by B&R. The electric drive parameters are listed in Tab. 2.

The electric drives for joints J1 – J3 are very compact gear–motors with positional feedback sensors. The gearboxes are very precise with zero backlash, as is common in the robotic industry nowadays. This is a key property for the precise positioning of the end point (a printing head). Furthermore, this solution is the best given the ratio of mass and nominal torque of the actuators in joints J1 – J3. These drives are by Harmonic Drive.

Name	Type	Torque [Nm]	Current [A]
J1	CanisDrive – 58A–160	1840	8.5
J2	CanisDrive – 40A–160	841	7.2
J3	CanisDrive – 32A–100	433	9.1
M1–M4	8LSAA2.D9045S200–3 motor 8GA40–060—003S2J3 gearbox	3.81	1.31
Z	8LSA25.D9060S200–3 motor 8GA40–060—064S2L2 gearbox	33.28	0.71
E	will be defined later	–	–
T	will be defined later	–	–

Table 2. Electric drives parameters

2.2 *Robotic arm control system*

The control system topology is shown in Fig. 5. The system is divided into four switchboards: HR1, HR2, PR1 and PR2. The connection between all the drives, the IO and the PLC is achieved using the real–time bus POWERLINK. This means the control system can work as one complete entity despite its division into four parts.

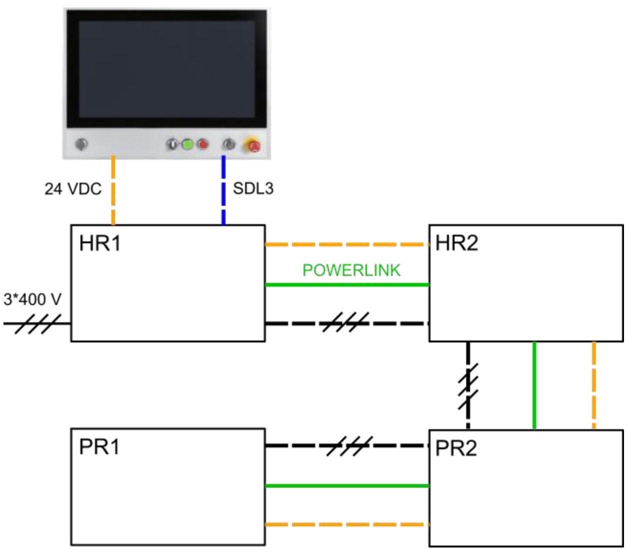

Figure 5. Control system topology – power supply and bus connection

All data communicated via POWERLINK is synchronized every 400 μs. All axes can be moved in a controlled path at the end of the robotic arm thanks to this synchronization. The hardware connection is achieved by a standard Ethernet cable CAT5. This simplifies the installation with regard to the movable parts on the robot.

A power supply must also be provided for the robotic arm. The power supply parameters are 3x400 V / 16 A / 50 Hz. This voltage is connected through all switchboards in our design. All ACOPOS units are connected to this power supply. ACOPOS is a servo–controller for electric motors. This can convert power supply energy to control movement at a shaft of a motor.

The internal switching board arrangement is shown in Fig. 6. All the switching boards have two main components: terminal blocks and ACOPOS 3. Some of them have additional parts e.g. APC 910 and IO modules.

ACOPOS P3 is a servo–controller with three axes (motors). This means it can control three motors independently. This 3–axis servo drive offers a power density of 4 amps per liter, making it one of the most efficient servo drives with integrated safety functions on the market. [B&R 2021] This power density gives us the opportunity to create designs with smaller cases for switching boards. This is not so important for a robotic arm in a scale 1:2 which is mainly intended for experimental work. However, for the future, for the final design of the robotic arm, the size and mass is very important for better maneuverabilty on site.

HR1 description: This switching board is equipped with APC 910, safety IO and a power supply of 24 V. There is a terminal block for a power supply connection 3x400 V. The Safety module (PLC) controls both the speed of the axes and some of the robotic arm's safety features, such as the laser curtains monitoring the working area. Safety on a construction site is a big topic for future research, but it is not a task within our present research. We can implement some simple safety features while conducting experiments, but not, presently, for a construction site.

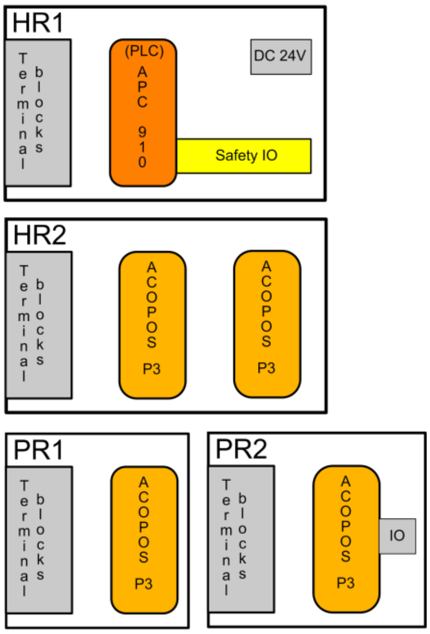

Figure 6. Internal switching board arrangement

HR2 description: There are two ACOPS P3 units for 6 axes. Four of them are used for M1–M4 for lifting the base of the robotic arm. Two of them are reserved for possible future use.

PR1 and PR2 description: These two switching boards are very similar. Each has an ACOPOS P3 inside. Breaking resistors are connected to ACOPOS' P3 DC bus to allow the dissipation of energy from the robotic arm during slowing down periods. PR2 also has an IO module. This IO module is equipped with different DI, DO, AI and AO modules. The 3D printing of cement mixtures needs some sensors e.g. pressure sensors, laser sensors (measuring distances), humidity sensors, temperature sensors etc. These sensors are related mainly to the printing head and the printing quality.

The robotic arm control software has been designed to use modified models designed in Matlab/Simulink, using B&R Automation Studio Target for Simulink, allowing their easy to use implementation into the target control system – an Industrial PC.

This solution enabled us to design a robotic arm control in Matlab/Simulink allowing the use of all available tools and toolboxes on offer from Matlab (eg. Robotic Toolbox). Designed, debugged and modified simulation schemes are automatically transferred by Simulink Coder® or Embedded Coder® into a source code in C/C++ language. Therefore, the need to write the program manually is eliminated [B&R 2019].
Fig. 7 shows the process of implementing control based on models designed in Matlab/Simulink.
The model–based control software consists of trajectory generation layers and a motion control layer. In the trajectory generation layer, an automatically generated Simulink task is used to solve the direct and inverse kinematics of the robotic arm and to implement interpolation functions (eg. Spline functions).
In the motion control layer, the automatically generated Simulink task is used for centralized control of the robotic arm for dynamically demanding applications.

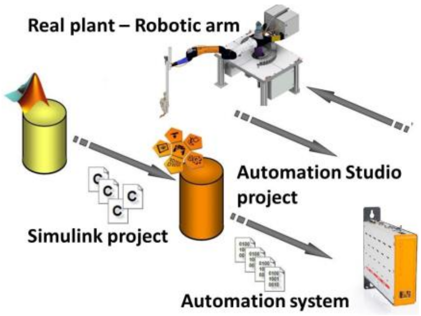

Figure 7. Simulink model based control implementation process

3 RESULTS

3.1 Robotic arm design results

The resulting designs obtained from the generative design algorithm are shown in the charts below. These charts represent the resolution values of the displacement of endpoint and mass of a given segment in each iteration. The blue dot in the chart representing individual iterations. The red dot represents our chosen iteration. In all of our chosen iterations, the safety factor was greater than 2.5.

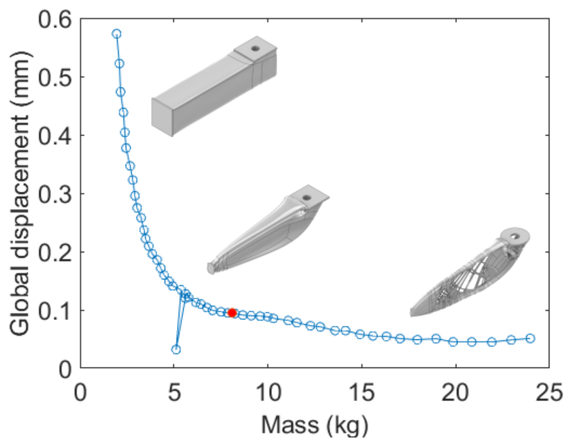

Figure 8. Results from the generative design algorithm for link 3

In the case of the design of link 3, displacement of the endpoint was not decisive, nor was there a large requirement for link rigidity, but there was a requirement for the lowest weight.

From our point of view, the selected design represents an optimal solution in terms of weight, endpoint displacement, rigidity and safety factor. Generative design results for link 3 are shown in Fig. 8. Available solutions with lower weights were already achieving too high a displacement of endpoint due to the saving of weight.

Iteration number 21 was chosen for the design of link 2 with a mass of approx. 48 kg and displacement of the endpoint of approx. 0.25 mm. Generative design results of link 2 are shown in Fig. 9. This iteration represents a suitable compromise between the mass, rigidity and deflection of the endpoint. The safety factor was greater than 2.5.

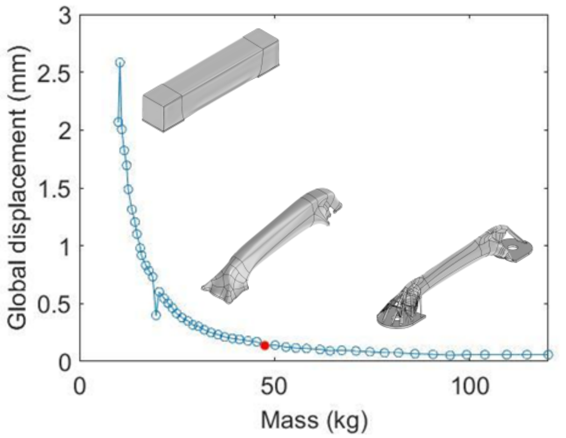

Figure 9. Results from the generative design algorithm for link 2

Link 1 was designed to meet the maximum rigidity requirement regardless of the total mass. This request was accepted because the first link has the greatest impact on the displacement of the endpoint of this assembly. For this reason, a design of about 100 kg and with a displacement of about 0.2 mm was chosen. Generative design results for link 1 are shown in Fig. 10. The safety factor of this design is greater than 3.

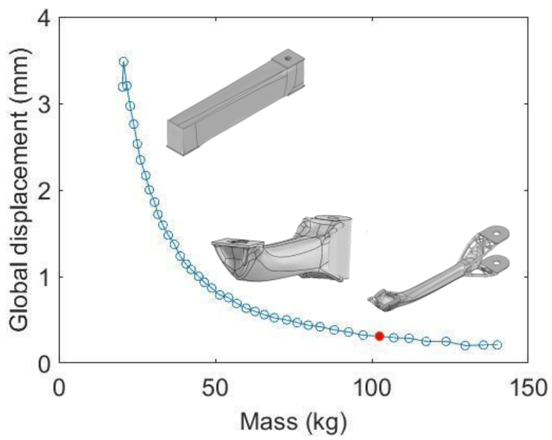

Figure 10. Results from the generative design algorithm for link 1

Although the properties required by the selected process are validated in the manufacturing process, and the generative design algorithm is based on machine learning and artificial intelligence, the software occasionally fails to generate shapes that cannot be made [Buonamici 2020]. As a result, we have made design modifications to the link shapes selected from the generative design to account for manufacturability, drives placement, cable routing and other accessory requirements. Fig. 11 shows the final design of each segment after the modifications have been made.

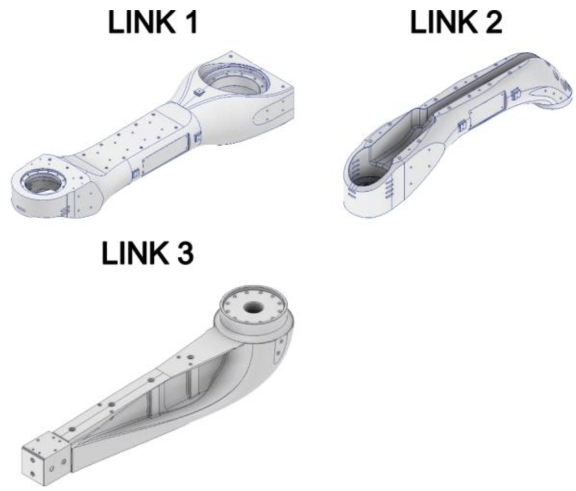

Figure 11. Links results based on the generative design algorithm

The design modifications made to the shapes have naturally caused a change in the mechanical properties of the individual links. Considering the design process, which proceeded by the sequential design of the individual links, verifying the achieved displacement values for the whole robotic arm was also necessary. To this purpose, we conducted detailed FEM analyses of the entire robotic arm at previously identified positions causing significant loads, shown in Fig. 3. The results are shown in Fig. 12, 13, 14 correspond to these positions. The red arrows represent the weights of the switchboards and the load at the endpoint. The yellow arrow represents gravity. The green arrow replaces the actuator motor, which was not included in the model.

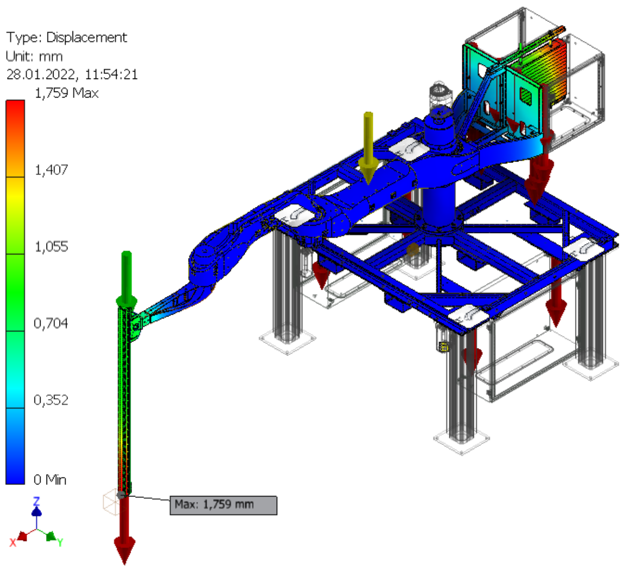

Figure 12. Global displacement result for the robotic arm at first position causing significant loads

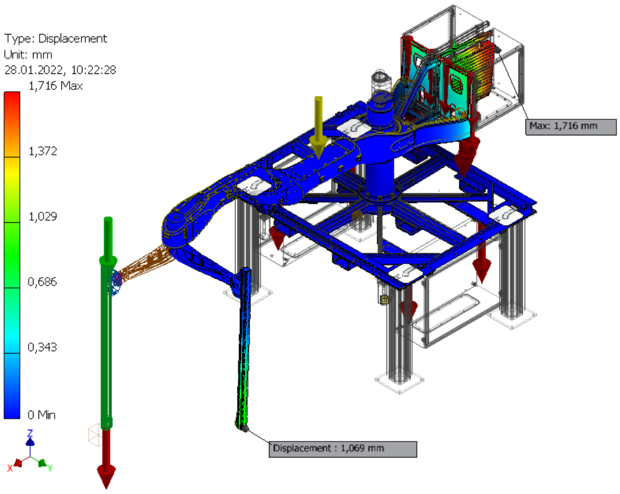

Figure 13. Global displacement result for the robotic arm at second position causing significant loads

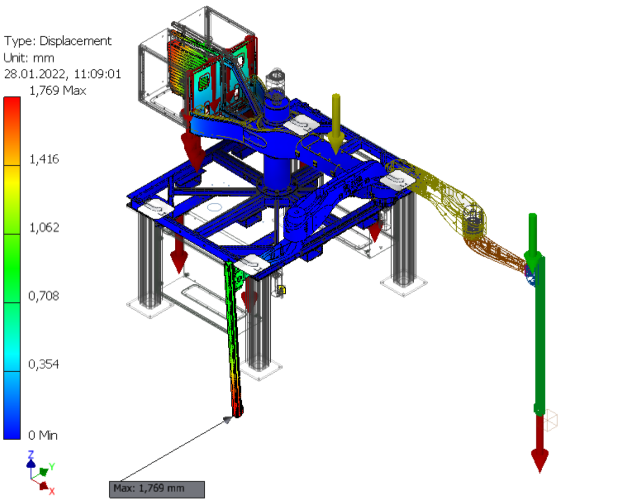

Figure 14. Global displacement result for the robotic arm at third position causing significant loads

3.2 *User's software to control robotic arm*

The user's software control is provided by the mapp Technology system – mapps for short. These are as easy to use as a smartphone app. Rather than write lines and lines of code to build a user management system, alarm system or motion control sequence from the ground up, developers of machine software simply configure the ready–made mapps with a few clicks of the mouse. Complex algorithms are easy to manage, allowing programmers to focus entirely on the machine process" [B&R 2021].

In the software, we use three layers of mapp – mapp Motion, mapp Services and mapp View. The block schema with layers is shown in Fig. 15.

Mapp Motion:

The robotic arm and the table is represented by seven servo synchronous servomotors. In the software, each motor is represented by a function block MpAxisBasic, shown in Fig. 16. This function block is connected with the visualisation via the OPC UA server and provides basic movements for manual axis control.

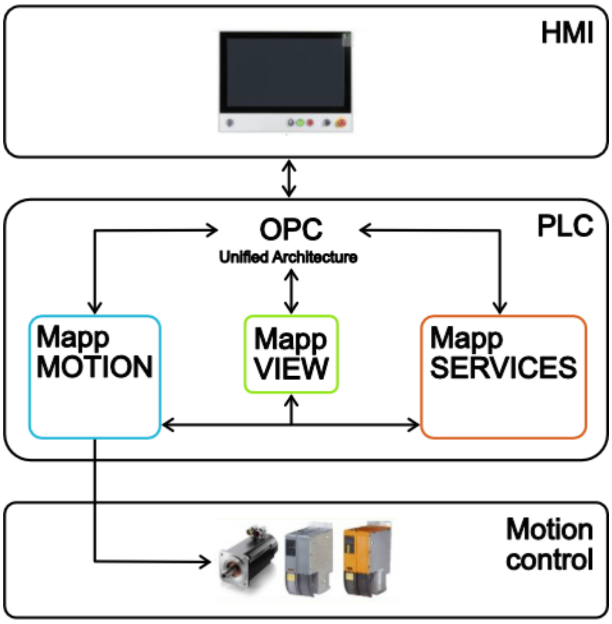

Figure 15. Robotic arm control system overview. [VOJIR 2021]

The axis control software in manual mode must include collision protection against mechanical damage, which still calculates the robotic arm's direct kinematics, comparing the cartesian coordinates table with the tool. In this case, when the tool is near the table, the velocity of the robotic arm is slowed down. The maximum rotation of each arm is limited by the axis limits.

More advanced control of TCP (Tool center point) and Trajectory generator uses the basic FB MpAxis Basic, together with special model based control programs created in Matlab Simulink.

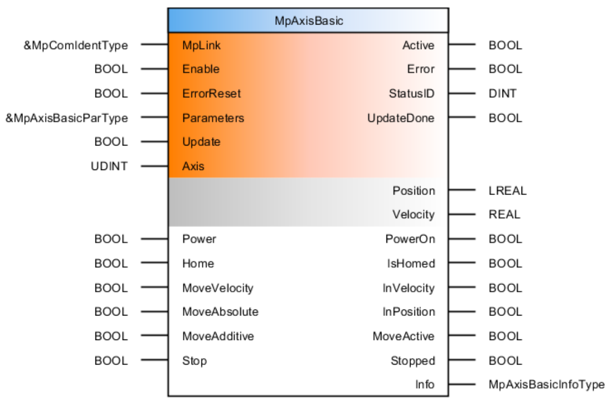

Figure 16. Function block MpAxisBasic

Mapp Services:

The other important part of the software is mapp Services, which includes Alarm management, Event management and User management.

Alarm management collects and manages mapp alarms and user alarms. The alarms are configured using Automation Studio, are managed in the application and then displayed in an HMI. In this case, when any axis alarm is active, all movements are stopped.

Event management can be used to log various events e.g. user-defined events, MpUser, change OPC-UA variables etc. The Audit system programming is realized by the MpAuditTrail configuration file and a system of text files. The final audit is shown in the HMI or is saved in the export file.

User management includes access rights, password changes and create or remove roles/users.

Mapp View:

The last important part of the software is mapp View. Mapp View is built on HTML5, CSS3 and JavaScript. It uses data on the OPC UA server and displays it in the HMI application via the design pages and widgets, shown in Fig. 17 and Fig. 18.

Our application uses a very important widget Paper, which shows the real–time position of the robotic arm. The SVG picture of the arm takes over the angular rotation from the real model and animates it in the visualisation.

The layout of additional widgets allows the operator to effectively control the robotic arm, alarms, audits and intervene in the user system.

Figure 17. Detail of HMI main page with robotic arm control

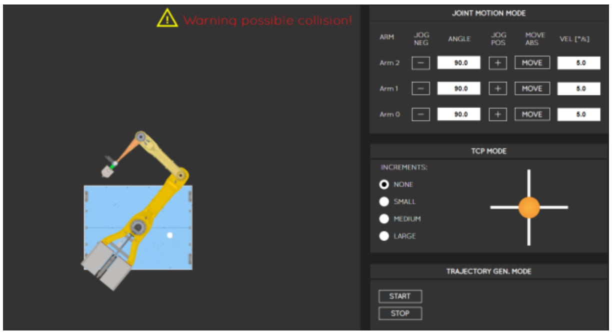

Figure 18. Detail of HMI main page with robotic arm control in possible collision state

Thanks to these 3 layers of map components, we can efficiently, and in a short time, create control software for the robotic arm. The machine's end operator, who will see only the last layer of software – visualization, will appreciate the easy and designed control of the HMI application, which can be opened in any Web browser.

3.3 Resulting robotic arm

The proposed robotic arm is a SCARA structure with an added rotational axis structure, reaching a total length of 2.8 m. It is capable of handling a load placed at the end of the arm up to a maximum of 35 kg. The arm itself is composed of three segments and a balancing arm. At the end of the arm is an actuator with the possibility of achieving a vertical displacement of 1000 mm. The entire robot is mounted on a chassis with four lifting columns that allow the robot to be lifted up to 2500 m. The experimental robotic workplace is shown in Fig. 19.

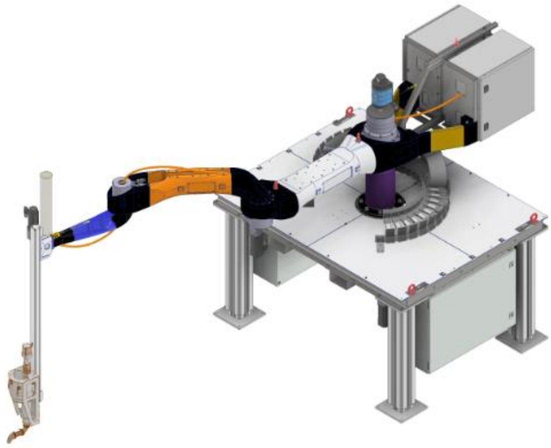

Figure 19. Experimental robotic workplace overview

The individual arm segments are designed using a generative design process and for manufacture on a CNC milling machine. The dimensions and weights of the individual links are listed in Tab. 3.

Links	Length [mm]	Weight [kg]
Link 1	1100	104.2
Link 2	900	49.1
Link 2	800	8.3

Table 3. Links parameters

Segments are connected in joints by rotary actuators. To compensate for the overturning moment the arm is equipped with a balancing arm, which is made up of steel parts and electrical switchboards. The manufactured robotic arm without switchboards is shown in Fig. 20.

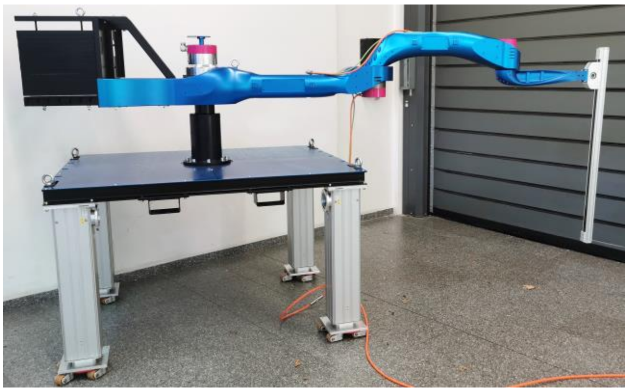

Figure 20. Robotic arm photography

The robotic arm control system is designed as a distributed composition of electric drives and four switchboards. The heart of the control system is an industrial computer APC910, with an installed hypervisor, allowing it to run a real–time operating system (Automation runtime), and a general operating system (Linux or Windows), simultaneously.

The general operating system allows us to design models of building blocks and convert them into CNC programs (G–code), which can then be run by the real–time OS called Automation runtime. The general operating system can also serve as a gateway to IoT in the way that it can transfer data from the real–time system into the OPC UA server or the cloud [VOJIR

2021]. The control system is based on B&R (member of ABB Group) components. Electric drives are by Harmonic Drives.

4 CONCLUSION

Different variants of cement mixtures printing solutions for building construction are currently under development, as described in the introduction of this paper. We mentioned solutions that use cartesian robots or robotic arms. In our opinion, each solution has its advantages and disadvantages. We predict that the coming years will see the development of these new approaches in the construction sector and we assume that, above all, the market will show what solutions will really be adopted and put into practice on a wide scale. At the same time, it will certainly be a difficult and thorny path for such innovative approaches in such a conservative sector.

We presented the assignment of designing an experimental robotic arm for the experimental development of printing cement mixtures as the chosen solution for our approach in the development of printing cement mixtures. The challenging task was the design of a 2.8 m long arm with the ability to handle a load with a maximum weight of 35 kg. In the introduction, from a mechanical point of view, we asked questions about which design method is adequate for such an assignment and asked concisely if it is appropriate to use a generative design process for such a large and complex assignment. In our work, we went through the detailed process of generative design of individual robot links.

From our point of view, we can say that, in our case, the use of generative design was indeed very beneficial. At the very beginning of the design, we needed to decide what elementary shapes should be chosen for the design of the individual robot links. By using a generative design approach, we were able to analyse the various initial ideas for arm shapes within a short period of time, with different approaches influencing the manufacturing technology. We are certain that in the case of standard design of different shapes using the classical method of CAD, this initial phase would have taken considerably longer and we would probably not have been able to examine all the initial ideas. We should note that the design results were greatly influenced by the initial boundary conditions. It is therefore not always possible to immediately take on board the first partial results obtained, and the task needs to be studied in detail, in advance, from point of view of constraints, loads and subsequent adequate ways of entering these parameters into the analysis. The resulting shapes need to be analysed and modified according to planned manufacturing technology, with a necessary follow up strength analysis required to validate the results and ensure that the resulting component actually meets the input requirements.

Once we had decided on the CNC machined shapes, it was very important to quickly establish the basic dimensions of the cross-sections of each link. In the final design phase, generative design helped us optimize the link shapes to achieve the desired rigidity combined with the lightness of the structure. The input requirement for maximum endpoint displacement was up to 3 mm. Due to the effective deployment of generative design in the design process, we can conclude that the designed robotic arm meets this input requirement based on the results from the FEM analyses at the positions causing significant loads on each link. The results of the FEM analyses indicated endpoint displacement values up to 2 mm. Thus, from our perspective and experience, we can conclude that the generative design approach brought benefits, even in such a complex task, to get the job done. Especially in innovative, less researched, applications, it is a powerful tool.

The proposed experimental robotic workplace will be used as a starting point in the development of a 5.6 m long robotic arm designed to print cement mixtures on a construction site. The workplace will certainly make available further research into cement mixtures printing technology, kinematic structures and drive control systems, printing mixtures and robot site navigation.

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