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Centralized-distributed Integrated Demand Response Method for Industrial Park

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ABSTRACT

An attempt was made to build a simple and low-cost device capable of positioning 3D prints for the process of additive manufacturing to conveniently allow the desired extend of the existing 3D printing capabilities. 3D printing with the use of increased number of axes, as compared to the standard approach, can eliminate such disadvantages of FDM technology as orthotropy of prints, surface roughness, and the consumption of both time and material devoted to make support structures. A CAD design of a parallel manipulator, used as a positioning table (platform), was developed, which was used for numerical simulations, and then a physical manipulator was made. The table was tested independently, i.e., as a stand-alone device, and, next, in cooperation with a 3D printer which allowed to obtain non-planar prints. The obtained results allowed for both the identification of problems related to multi-axis 3D FDM printing and an attempt to formulate concepts enabling to overcome them via adequate design and control modifications. The raised conclusions will be used to further development and more comprehensive understanding the phenomena that are present during the investigated manufacturing process.

1. INTRODUCTION

The Fused Deposition Modeling (FDM) 3D printing technology has found its application in many branches of industry and has become a fully-fledged manufacturing method that is already used by many engineers. It has its advantages and disadvantages, but they are not a certainty, because its capabilities are constantly being expanded and disadvantages eliminated [1]. This paper proposes the concept of using a low-cost solution that would expand the characteristics of 3D FDM printing. The described project aims to provide the opportunity of achieving non-planar printing for every user of a standard 3D printer. The mechanical design of the device, its analysis and development of the control system are presented. Finally, the authors present a prototype of the mechanism, which they tested as the tool for non-planar 3D printing. The presented project was accomplished in cooperation with the company GOODFIBERS sp. z o.o.

The content of the current paper is as follows. In the second chapter, an overview of the published papers related to the topic of non-planar printing is presented. Next, the concept and design of a manipulator integrated with a Cartesian 3D printer is proposed in the third chapter. In the fourth chapter, the prototype of the device is presented and the results of the initial tests for the manipulator orientation control are reported. In the fifth chapter, the method of creating a program dedicated for 3D printing with the use of the newly constructed device and the final 3D prints are presented. In the sixth chapter, the conducted work and proposals for further tests with the use of the manufactured device are summarized.

2. STATE OF THE ART

The concept of non-planar 3D printing evolves in many different ways. The description of the first research conducted in this area is dated for the year 2007 and the term Curved Layer Fused Deposition Modeling was introduced [2]. The first results showing non-planar prints were presented three years later [3]. Since then, many concepts for the creation of non-planar prints have emerged. The significant and not yet experienced factors that may be positively identified and advantageously used during a printing process with this way of modeling were also found. Various attempts were also made to deal with the defects of prints in FDM technology by removing the support structures [4], improving the quality of surfaces (addressing the common but undesired stair-step effect) [5,6] and increasing the strength parameters of prints [7,8].

In terms of hardware, various kinematic structures of 3D printers have been used thus far, allowing for the manufacturing of non-planar prints. The existing limit regarding feasible geometric configurations for a typical Cartesian 3D printer is a simultaneous use of all available 3 axes (for linear motion) of the device. This type of approach does not use additional equipment, but is very limited, due to the fact that typical printers are adapted in their construction to printing in the so-called 2.5D, i.e., with a gentle movement in the Z axis [9]. A solution to this problem is, for example, the use of elongated nozzles, which is used by the Kupol Inc. [10]. Another approach is an application of 3D printers with additional degrees of freedom in the form of a rotating positioning table or a rotating head [11]. Similar configurations are used in 5-axis milling machines [12]. The advantage of this solution may be the installation of the platform in a closed, heated chamber, which increases control capabilities regarding the properties of the printed material - as opposed to the solutions based on manipulators. The last solution that gives great possibilities in achieving demanded position and orientation is the use of industrial manipulators with an extruder as a working tip [13]. However, the use of robots in additive manufacturing goes beyond the known non-planar cases [14]. There are also many new ideas of how additional degrees of freedom can help to achieve multi-axis additive manufacturing [15]. The above referenced research helped in choosing an adequate kinematic structure for this paper.

In addition to many design solutions, there are also known various concepts for generating tool paths for the above-mentioned type of 3D printing [16]. In fact, there are many ways to build path generator and it seems difficult to find a solution that would be optimal for each geometry of the printed object [17]. So far, the most convenient and efficient way is to create dedicated paths to given shapes with regard to the application. The final decision may be influenced by aesthetics, printing time, the need to use support structures or mechanical strength required [18].

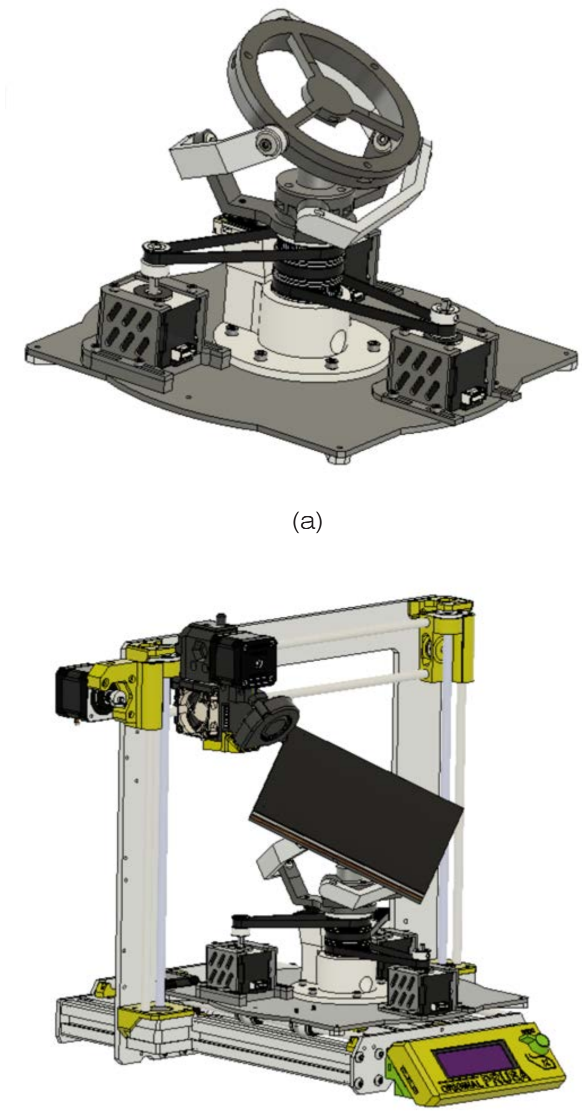
Some of the published works focus on cutting 3D models for non-planar printing based on decomposing and regrouping of the shape of the model to create sections that are 3D printed in different orientations [19]. Other papers focus on shapes created with a single shell [20]. This is the approach that will be used in this paper. Creation of paths later transformed into G-Code is possible with the use of a graphical programming in Grasshopper [21], which was also used in this work.

There are many application areas where non-planar printing can be used and where it can introduce new possibilities. There are applications related to the use of concrete to create large structures [22], fast prototyping using thermoplastic materials [23], metal 3D printing [24] or even used in creating auxetic lattice shells [25]. Non-planar 3D printing can also have a positive impact on the environmental aspects of prints and be more eco-friendly [26].

3. CONCEPT FOR POSITIONING MANIPULATOR

The idea of using a parallel spherical manipulator as a working table has been considered by the authors of the present work to conveniently addresses their current demand for additional degrees of freedom in a 3D printer, that, in effect, would enable implementation of a non-planar printing. This is justified by the authors' desire to create a mechanical add-on to a 3D printer that allows the user to perform non-planar prints in a low-cost way, extending the existing capabilities of the 3D printer. Parallel manipulators are primarily used for fast and precise positioning movements, which is also required for 3D printing. The selected kinematics of the manipulator provides additional 3 degrees of freedom needed for positioning the 3D printed parts and the additional functionality of an infinite number of revolutions around the Z axis, which can be considered a useful feature. The design assumption is also the low overall dimensions of the table and the ease of installation the positioning component in a 3D printer. The above-mentioned assumptions allowed the authors to start designing actuators of the developed device.

The design of the platform was made with the use of CAD software - Fusion 360. The manipulator was adapted to the shape and dimensions of the Prusa i3 MK3S printer heated bed. Installation by replacing the heated bed with the manipulator base is easy to perform. The number of mechanical parts of the designed structure has been reduced to a minimum, while ensuring the possibility of appropriate cable routing to the new heated bed located on the manipulator. The motors enabling the required mobility of the device are arranged on the plan of an equilateral triangle. The movement on the arms is transmitted by toothed belts and racks mounted on a common shaft in the center of the positioner. The design of individual elements of the structure has been optimized for easy and quick prototyping by printing most of the parts in FDM technology. The design of manipulator as well as the Prusa printer equipped with the developed construction are presented in Fig. 1 as CAD views.

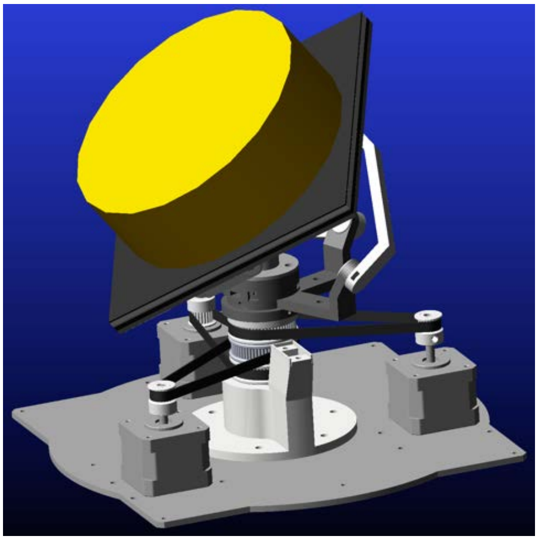


(a)

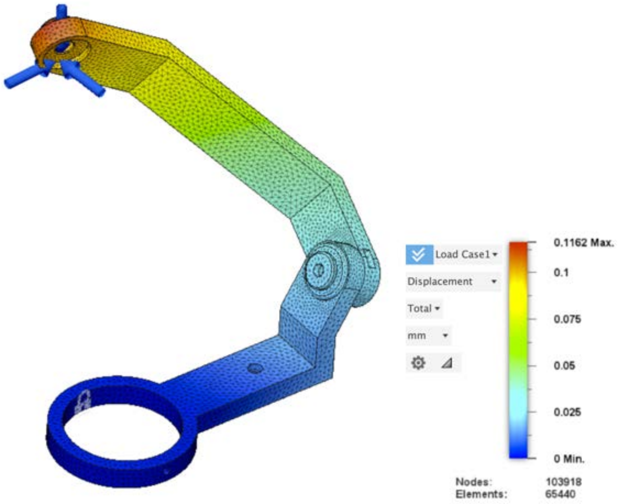
(b)

Fig. 1: Developed manipulator: (a) design, (b) assembly with a 3D printer.

In order to verify the required functionality of the developed technical solution, analyzes were carried out with the use of numerical tools. The MSC Software / Adams and Fusion 360 Simulation Workspace were used to analyze the manipulator's mechanical compliance. It has been noticed that the problem regarding the selected configuration of the manipulator may be the deflection of the arms associated with the increase in mass of the printed parts localized on the table during 3D printing. This may lead to a deterioration of the quality of 3D prints in terms of their geometric properties. The purpose of the compliance analysis is to answer the question of how large the observed deflection will be and whether it is acceptable during the 3D printing process. The most unfavorable position was arbitrarily chosen, with the mass of the printed element expected to have the greatest impact on the deflection of the arms. Reaction forces acting on the arm were determined on the basis of a simulation in the Adams program. The manipulator was loaded with an object located over the entire workspace of the device. The kinematic parameters of the motors were set to reach the angular speed of 135deg/s. The results of multibody simulation were then transferred into the Fusion 360 software to enable the next stage of the FEM simulation, as presented in Fig. 2. The simulation results for the arm made of aluminum are presented in Tab. 1.



(a)



(b)

Fig. 2: Numerical simulations: (a) Adams multibody simulation, (b) Fusion 360 FEM simulation.

Tab. 1. FEM simulation results – convergence analysis

ID	Average size of finite elements [mm]	Maximum displacement [mm]
1	12	0.07359
2	6	0.05973
3	3	0.09321
4	1.5	0.1162
5	0.75	0.1418
6	0.375	0.1455

The convergence of the FEM simulation results was found for the maximum value of the displacement of 0.14 mm. In the case of FDM technology, the standard layer height during the 3D printing process is 0.2mm. The identified maximum displacement is close to above-reported value, but it should be noted that the structure’s deflection will increase gradually as a printed part expands. It is possible to introduce software deflection compensation by changing the Z position (in a generated G-Code) taking into account current geometry of a component being 3D printed. However, for basic functionality tests (following the assumed scope of the work), the identified deflection is considered by the authors as sufficiently small and its impact was ignored for the present study.

The next stage of the described project was to design and build a control system that would allow the mechanical structure to move and achieve the appropriate platform orientation. Two systems were made for this purpose. The first task was to control the engines, and the second to verify the platform orientation using the IMU module. In both systems, Arduino microcontrollers were used, and the Arduino IDE environment was used for their programming. An additional optical sensor was used for the subsequent automatic positioning of the platform after turning on the power. A simplified electrical diagram of the device is shown in Fig. 3.

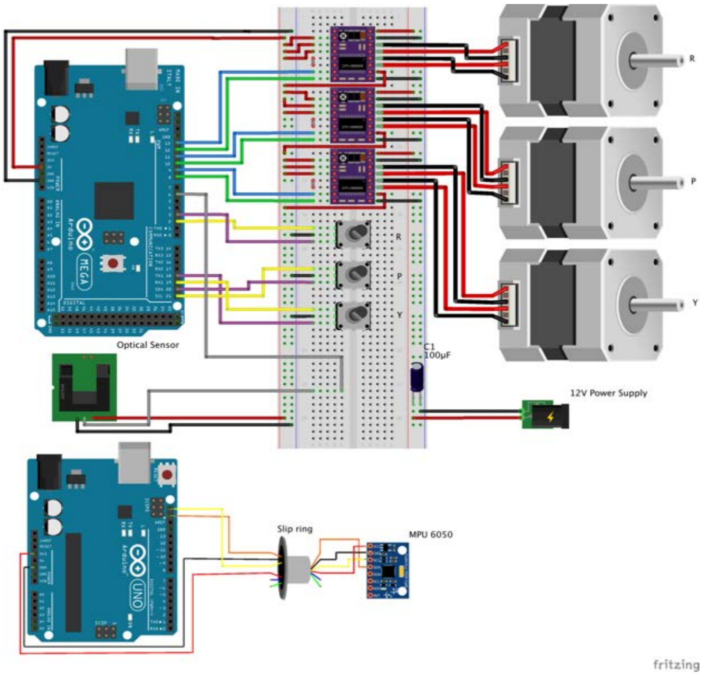


Fig. 3: Electrical diagram of the test stand made in the Fritzing program

4. CONSTRUCTION AND EXPERIMENTAL TESTING OF PLATFORM PROTOTYPE

The manipulator (the investigated positioning platform) was made of components available on the market and elements made on an FDM 3D printer. The prototype was built on the basis of a mechanical and electrical design and met the assumption of compatibility with the Prusa i3 MK3S printer, which can be seen in Fig. 4.

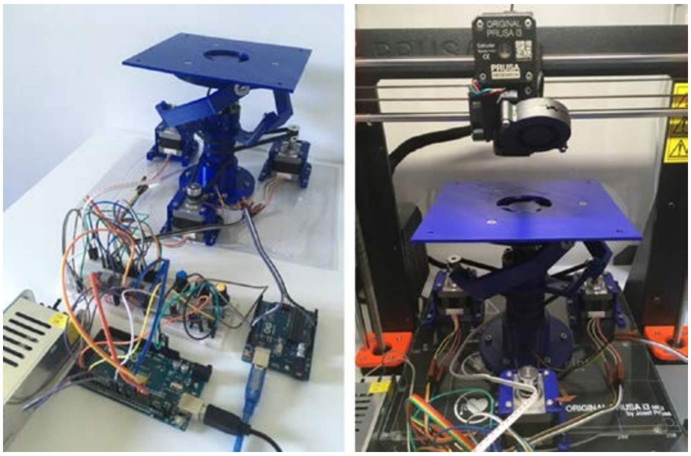


Fig. 4: Prototype of the developed technical solution.

The first experiment was performed to test manual motion control of motors with the use of encoders. The platform orientation data was transferred from the IMU module through the serial port to the computer and displayed on the screen in the form of RPY angles. A program solving the problem of inverse kinematics has been developed to fully verify the operation of the manipulator. It was written in the PyCharm environment in Python and was used to generate the values of motor angles for a given platform orientation. The results obtained from the program, converted into the appropriate number of steps, and then entered into the program in the microcontroller, made it possible to conduct another test. The elaborated program assumed the execution of 10 movements assuming that the positioner reaches the angular orientation RPY (30,0,0), and then returns to the starting state, i.e. (0,0,0). Tab. 2 shows the values of the Roll and Pitch orientation angles that were collected by the IMU module.

Tab. 2. The values of the angles collected during the test

ID	R [°]	P [°]
Start	0	0
1	27	0
2	28	0
3	28	1
4	27	0
5	28	0
6	27	0
7	28	2
8	30	2
9	29	2
10	29	1
Finish	0	0

Tab. 2 shows that the manipulator has returned to its initial orientation at the end of the job. On the basis of the obtained data, the inaccuracy in achieving the given orientation can be noticed. During the experiment, however, it was noticed that the data from the IMU module fluctuated within ± 1 ° even in the absence of any movement, therefore the errors could be related to the poor quality of the installed sensor. Moreover, the error may also result from geometric inaccuracies of the construction or from approximations in the calculations of the inverse kinematics problem. Despite the errors obtained, the assumed functionality of the manipulator related to its dedicated task, i.e., allowing for non-planar 3D printing, and maintaining orientation in space was confirmed.

5. 3D PRINTING TESTS

In the next step, the procedure of 3D printing of tube was elaborated making use of the constructed positioning table. The test used a 3D printer with a manipulator to perform a non-planar 3D print. Specifically, the test concept assumed a simple tube print for a 3D printer (Fig. 5), and a cyclic change of orientation by a small angle for the platform, so as to obtain a bent tube. The experiment was performed using the Grasshopper environment, which allows for graphical creation of algorithms with the use of blocks, integrated with the Rhino 3D program, in which the visualization part takes place. Grasshopper allows to create a script that generates commands for a 3D printer. The shape of the printing head motion paths was created with the help of several function blocks and a special block changing the lines to G-Code commands for a 3D printer with a Cartesian structure. Part of the script can be seen in Fig. 6.

The G-Code generated was transferred into the printer's memory, and then launched, simultaneously with the Arduino script that enables motion of the manipulator. After around 20 minutes, both programs were finished, and the 3D print of the tube was fully created (Fig. 7).

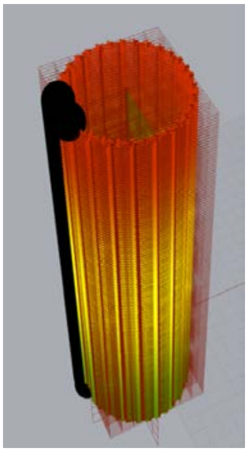


Fig. 5: Extruder paths for 3D printed tube generated in Grasshopper

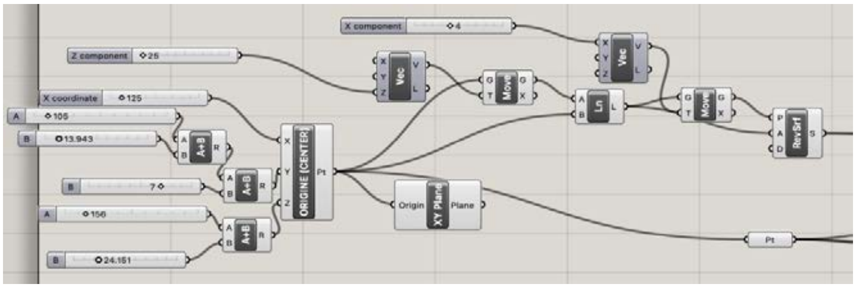
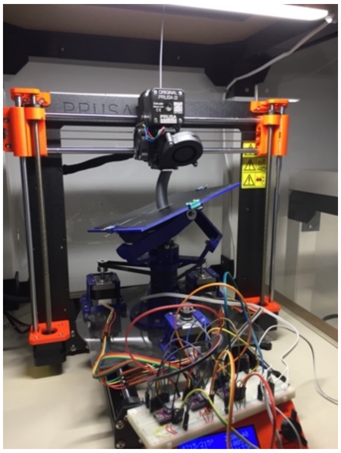


Fig. 6: Part of the script in Grasshopper that defines the shape of a printed component.

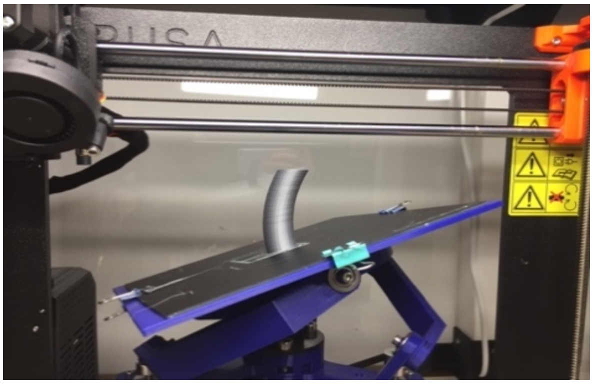


(a)

(b)

Fig. 7: (a) Manipulator in the process of the 3D printing, (b) 3D print of a bent tube.

After the present test, the first problem was noticed that there was material shortage in certain parts of the printed tube. This is due to the rotation of the manipulator, which causes the material to be compressed (overextrusion) on the inside of the fold, and there is no material on the outside (underextrusion). This phenomenon illustrates the first thing we need to pay attention to in case of non-planar prints. During multi-axis printing, it is not possible to assign a certain extrusion rate value to a given layer height. It is so since extrusion speed must continuously vary with the distance between the two overlapping paths so as to accommodate long distances and reduce material flow at short distances. Considering the observed phenomenon, corrections were made by the authors in the script written in Grasshopper. Additional code blocks allowed to modify the generated G-Code by adjusting the extrusion to the printed shape. In another experiment, the same tube was printed, but this time the filament flow was reduced on the inside of the bend and increased on the outside. The printed part obtained after code modification is visible in Fig. 8.



(a)

(b)

Fig. 8: (a) 3D printed tube, (b) comparison of the two test tubes.

6. CONCLUSIONS AND OUTLOOK

The manipulator integrated with the 3D printer, that was designed and constructed by the authors, met all the fundamental assumptions set for it related to its use for non-planar printing. The tests carried out showed that the desired orientation was properly reached and maintained. Thanks to the connection of the manipulator with a 3D printer, it was possible to perform an experiment showing one of its basic applications to demonstrate feasibility of the concept proposed in the work. The 3D print was made quickly and in acceptable quality, without the use of supports. Moreover, geometric distortions were not found after modification of the elaborated code. As of the planned future use of the constructed platform, it can be efficiently and conveniently used for 3D prints that would normally require support structures. Another future test may be the creation of non-planar paths that would improve the aesthetic characteristics by eliminating the staggered surface of 3D prints. Yet another application may be increasing the mechanical strength of the parts by arranging the material distribution perpendicular to the direction of the 3D printed layers, eliminating the anisotropy of the 3D print.

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