# Machine Vision for Auto Positioning in the Modular Industrial Equipment: A Case Study

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*Abstract*—**The unification principle of industrial equipment involves splitting the installation into interchangeable components, from which the required type of equipment is assembled for specific production tasks according to the order. For the common industrial equipment, zero position setting usually causes no issues. However, for the modular machines with different sizes of modules, the mounting error can be appeared and it has to be corrected automatically. In addition, due to a possible frequent change of equipment during the production process, clamps can wear out, increasing the error. It is necessary to introduce an automatic adjustment of tool position relative to the carriage suspension, implemented using machine vision systems. The cost of video capture equipment and computing tools decreases, and their characteristics, on the contrary, grow. Moreover, algorithms for recognizing markers' position and angle together with augmented reality development tools are also constantly being improved with their application complexity being significantly reduced, which emphasizes the practicability of their use. The paper describes the problem of eliminating the installation error of instrumental modules on a three-axes platform. The proposed method involves the use of a number of reference markers on the platform, its suspension, and on the plug-in modules.**

*Index Terms*—**Machine vision, Modular industrial equipment, Marker-based method, CNC, ArUco markers.**

## I. Introduction

The field of industrial production is an extremely dynamic and rapidly developing area of human activity. Current trends require an increasingly frequent change of a product range, as well as a gradual transition to personalized production, when even consumer goods are customized for a specific user.

All of the above leads to Research & Design works coming to the fore. There are more and more private design bureaus and organizations that are involved in producing high-tech devices and technologies to order. Such small innovative enterprises are usually called Startups. The goal of any startup is to design and test new products and bring them to the market as quickly as possible. Evidently, this requires an organization of a continuous cycle of prototypes development, and therefore, the availability of its own production enterprise.

The development of such experimental production is highly difficult for startups. Modern products are becoming more complex, combining both mechanical, electrical, and electronic components. The latter is especially relevant in connection with the rapid development of the Internet of Things and the Industrial Internet of Things, as well as with the widespread introduction of "Smart Technologies". The prototypes design of such devices requires a large number of sophisticated equipment units, so most startups in early stages of their development are forced to use the services of large organizations that have their own production facilities. This need leads to the following negative consequences:

- The cost of a prototype increases, since large enterprises are primarily aimed at the production of large batches and are ready to take a single order only if its cost is comparable to the cost of the batch. A typical example of the described situation is the production field of printed circuit boards. Here most of the order cost falls on the preproduction engineering, which is practically independent of the serial production.
- The prototype production time increases, since contacting a third-party manufacturer requires preparation of a full set of technical documentation, and involves coordination process, cost negotiations, etc.

These problems can be solved in different ways, for example, in the printed circuit boards production, the most common solution is the combination of orders from different manufacturers (which definitely has a positive effect on the cost of a prototype, but not on the production time). So-called core facilities and industrial co-working centers are also being developed. However, the concept of developing a modular equipment of the "office" class, which is characterized by lower accuracy and performance parameters, seems more promising.

Unquestionably, the main objective of a prototype is to clearly demonstrate the operability of a developed product. Prototypes are made in a single copy or in small batches, so the technology for their production may not be optimal. For example, the prototype of a case can be made on a 3D printer, and instead of a complex multilayer printed circuit board, several single-layer ones can be used. At the same time, modular equipment occupies much less production space and can easily be moved if the organization itself moves to a different place.

The paper describes the current development stage of a multipurpose modular platform for adjustable manufacturing equipment. The developed platform is a combination of chassis positioning the operating carriage in three-dimensional

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Cartesian space. On the carriage suspension various modules, that ensure the operation of the equipment, are mounted. By replacing the modules, various types of industrial equipment are created such as: equipment for the selective curing of photopolymers, drilling machines, milling machines, engravers, laser cutters, 3D printers, coordinate-measuring machines, machines for installing components on a printed circuit board, marking machine, sorting equipment, dispensers of chemical reagents, cartesian robots.

The developed platform is based on the principles of unification and hybridization. Unification refers to an open software and hardware architecture that allows creating new types of equipment and software on the basis of the "intelligent constructor set". Unification is achieved by dividing a single product into bigger interchangeable modules with each having a clear description of input and output parameters. To put it another way, a line of chassis of different overall dimensions and rigidity is being created for various types of equipment. At the same time, the principles of building electronic, electrical, mechanical, and software parts of each line representative remain invariable, and the transition to a new type of equipment is achieved by changing modules.

Undoubtedly, modules may vary in size depending on the problem being solved. Moreover, in accordance with the principle of unification, the control system must determine the position of the connected module independently and without the need for manual adjustment or calibration. It is known that processing accuracy depends on the accuracy of mutual geometric position of all components in industrial equipment. The latter is extremely difficult to achieve using the modular approach, since the position of the module with respect to the chassis coordinate system is not known in advance.

Higher positioning accuracy can be obtained by changing the way modules are mounted on a carriage suspension and, for example, using dovetail mounts with a wedge clamp. The described scheme is widely used in quick change toolposts of metalworking machines. This approach provides excellent accuracy and repeatability when reinstalling modules manually. However, it greatly complicates the overall suspension design, due to the need for high precision machining of mating parts (grinding is required for all mating surfaces in a joint), and the overall weight of the moving part in a system also increases. Furthermore, all modules must have the same dovetail mating part, depending not on the module size itself, but on the chassis dimensions. Consequently, the principle of universality is violated because in this case it is impossible to install a small-sized module on a large chassis.

It is also worth noting that one of the options for using modular equipment is to include it in flexible production lines, where automatic module replacement with the use of an industrial robotic arm will be required. The analysis of modern equipment has shown that sufficient pressing force for a wedge clamp can only be achieved using pneumatic clamps. This leads to the need of an additional air line, which also complicates the initial proposed approach. Instead, it is suggested to use a magnetic mounting system with an additional guide groove positioning on a plane parallel to the direction of carriage movement.

The described fastening system allows using modules of any size; however, the problem of combining the module and main chassis coordinate systems arises. In this paper, a combined automatic positioning system for a module on a carriage suspension using machine vision is suggested. This system determines the location of specialized optical markers on the chassis and automatically changes geometric parameters used in the control system.

The article is organized as follows. Section II is dedicated to an overview of related work. In Section III the description of the operational setup is provided. Section IV describes the methodology of research. Section V focuses on the results at this stage of development. The main limitations and drawbacks of the proposed approach are discussed in Section VI. Finally, Sections VII contains conclusions.

## II. Related Work

The application of machine vision is quite ubiquitous for today, especially within the industrial context. It is an essential part of industrial robotics that allows manufacturers to accomplish various tasks such as pick and place operations over different pieces [1], quality inspection [2], [3], human safety [4], etc. Besides, machine vision is getting relevant within CNC machine tools that are an integral part of manufacturing. A sufficient number of surveys are carried out regarding marker-based methods.

Researchers from Aarhus University [5] combine augmented reality and markers to create a CNC system for the laser cutter. The system is based on the WYSIWYG approach, where a projector is used to depict current contours, and markers are used to set its position on the working area. Along with that, Keio University specialists [6] expand the fiducial markers functionality for a laser cutter. To set cutting parameters, they put a set of fiducial markers near the workpiece, including material, operation order, and command markers.

In [7] a contouring error detection method based on machine vision is described. A special measurement fixture covered with markers is designed that allows researchers to measure contouring error without a cross-grid encoder.

Moreover, verification of the machining process is one of the tasks that can be addressed using machine vision. It includes collision avoidance of moving parts of the machine, tool cutting into the workpiece or fixture, and tool breakage. Commonly, a special software simulation that needs a detailed kinematics model is usually used for these purposes. However, such a method is not suitable for modular equipment.

Work [8] provide a method for a direct on machine tool processing simulation. Special markers are glued to the machine to determine tool and workpiece position, and augmented reality is applied to simulate toolpath and workpiece processing. Nevertheless, modular equipment requires the determination of the geometric parameters of the modules and working area on the fly. Thus, an additional study is needed.

## III. Operational setup

The proposed system for the automatic module positioning is a further development of the architecture of the modular production system described earlier in [9], [10], [11]. In accordance with this concept, a machine vision module is mounted on a chassis along with other modules used for processing (Figure 1). Nevertheless, the presence of this module is not mandatory, because it is needed only for those operations that require machine vision capabilities. In particular, it helped to solve the problem of determining the position of a workpiece by tracking reference points located on it [12].

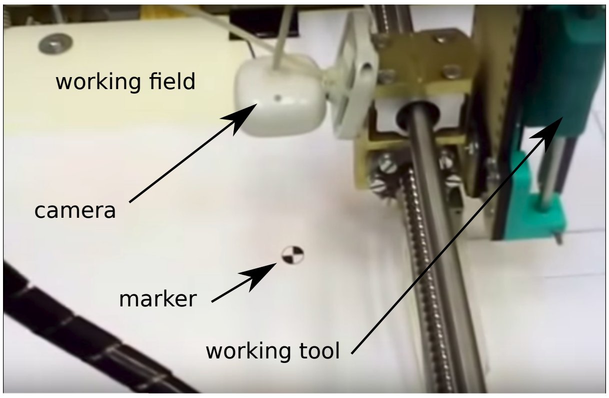


Fig. 1. Marker detection system prototype.

However, this system has a number of significant drawbacks. In particular, the method of quick module reinstallation on a carriage suspension is not implemented. The modules are mounted on screw connections, and after installing each module, it is required to manually input the optical axis offset value of the machine vision module relative to the instrument axis. In other words, the task of determining the exact position of a module on the suspension of a 3-axis platform is solved only mechanically and requires additional actions from an operator.

Currently, a new construction has been developed to simplify and automate the reinstallation of modules using magnetic mounting on a plane with an additional groove. Standard machine mounts with switchable (on/off) permanent magnets that have a separation force from 30 to 160 kg are used for experiments (Figure 2).

With the described configuration, the initial scheme with the camera being on a moving suspension does not allow precise module positioning with respect to the base coordinate system of a 3-axis platform. Modules can have different sizes, so the processing area can also change. In this case, the exact location of an actuator (a spindle axis, a laser head lens, a probe of the measuring module, a nozzle of a three-dimensional printing module, etc.) remains unknown at the stage of module connection. Moreover, the location of the module with a camera on a carriage suspension makes it impossible to see the entire work area fully. The carriage must be moved to find markers and determine their exact position, which takes extra time during module initialization.

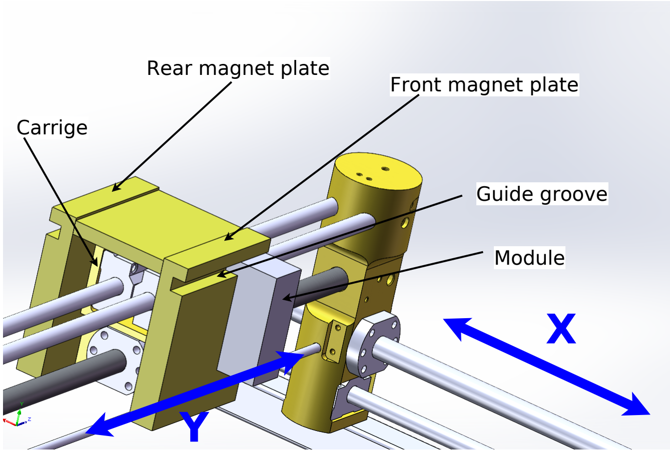


Fig. 2. Carriage design.

Therefore, a second camera is included in the new construction, located above the work area. This camera has a larger viewing angle, which allows determining the modules position with respect to the carriage and corners of the work area. Consequently, an additional upper camera is used to automatically position the modules with respect to the coordinate system of the 3-axis platform. On the contrary, the camera, located directly on the carriage suspension, is responsible for automatic instrumental equipment (machine vise, angle plate, jig, etc) positioning relative to the coordinate system of the 3-axis platform and part positioning relative to the machine tool (Figure 3).

Markers are made of polished stainless steel plates and mechanically attached to parts of a three-axis platform and instrumental equipment. Currently, images are applied by using ultraviolet printing. Experiments on the use of electrochemical blackening of stainless steel are also being conducted. Mechanical attachment of markers is preferred over gluing. The possibility of applying markers using laser engraving directly during the manufacturing process is also considered. This will increase the positioning accuracy and eliminate the need for manual tagging.

## IV. Methodology

### A. The selection of software development tools

The task of positioning by using optical markers relates to the field of augmented reality. There already exist a sufficient number of fully developed software libraries that implement the solution to this problem. The most well known one is OpenCV [13], [14], an open source library for computer vision. It has a convenient set of tools that simplify such routine procedures of machine vision systems as receiving a video stream from various external sources, camera calibration, image filtering, etc. In particular, this library has already been used to determine the position of a workpiece on a table and receive its coordinates using the Canny edge detection filter [12].

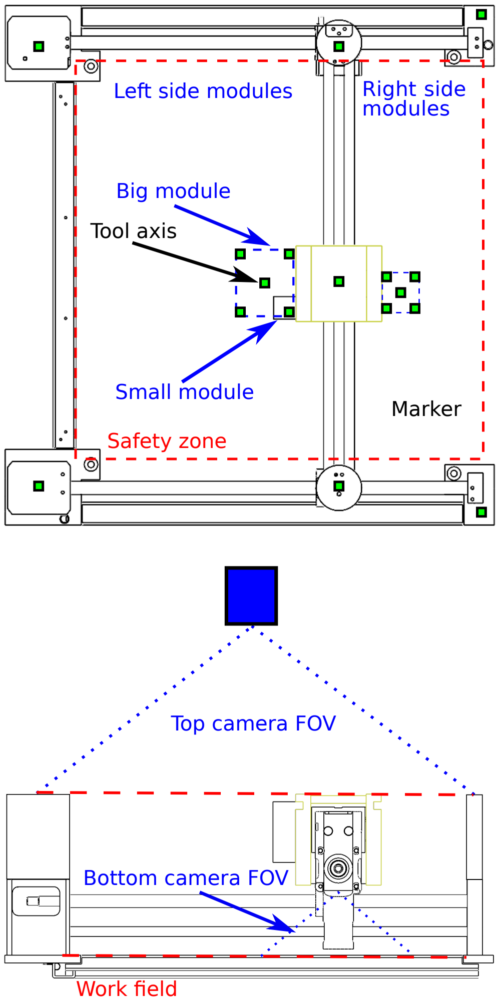


Fig. 3. Layout of cameras and modules.

To solve the current problem, the following requirements for the optical marker recognition software library were defined:

1) The library should be based on the OpenCV functions.
2) The library should be able to recognize markers by using a special dictionary.
3) The library must consider optical parameters of a camera (distortion, optical axis tilt, etc).

Markers should be simple enough for manufacturing (black-and-white markers with simple geometry, which can be made by UV printing, laser engraving or electrochemical blackening, are preferred).

Several software libraries that met the specified criteria were analyzed. Some of them are used to recognize markers that store data in binary form (Data Matrix, Maxicode, Quick Response Code). The described markers are convenient for creating an arbitrary dictionary when each marker describes itself. However, for the particular task under consideration, this possibility is redundant, because for the complete description of the 3-axis chassis geometry only 50 markers are required.

Therefore, application of dictionary encoded markers is appropriate. Firstly, in the case of its usage, an array containing the same type of markers is generated. It is important that the condition of maximum dissimilarity of markers is satisfied in order to simplify the recognition task.

All dictionary encoded markers can be divided into the following conditional categories [15]:

- markers consisting of square and rectangular components (ARTag, Cybercode, Matrix, ArUco, AprilTag, Visual-Code);
- markers consisting of circle and arc elements (TRIP, RUNE-Tag, CCTag, Intersense, BinARyID);
- markers with mixed elements, including complex shapes (ARTollkit, STag, ReacTIVision, SCR, SVMS).

Each of the listed marker types has its own advantages. In particular, circular markers show better performance when determining points (for example, in three-dimensional scanning systems), the rectangular type is optimal for determining planes in three-dimensional space, and mixed markers are best for high accuracy recognition in difficult conditions (poor lighting, overlapping markers, etc.). Unquestionably, rectangular markers are the most suitable for the considered system of automatic positioning of modules. Therefore, after the literature research and a series of experiments, the ArUco [16] was chosen as the main software library for the recognition process.

The ArUco library allows implementing a system for pose estimation, based on binary square fiducial markers. The main advantage of these markers is that the presence of only one marker in the camera's field of view allows an accurate determination of the camera's position relative to the plane where marker is located. Moreover, the guaranteed asymmetry of each marker makes it possible to determine not only the coordinates of the marker's center but also its angle of rotation. To sum up, with ArUco markers it is possible to obtain the exact location and direction of coordinate axes in a Cartesian space, which is extremely important for the problem under consideration.

### B. Camera Positioning and Calibration

To implement an automatic positioning system, it is necessary to solve two main tasks:

- *Proper camera placement*. The camera must capture the entire work area and at the same time not interfere with any working equipment.
- *Camera calibration*. The process of camera calibration lies in obtaining its intrinsic parameters and distortion coefficients. These parameters remain constant until the camera optics are changed, so the camera must be calibrated only once.

To obtain the most accurate result during the optical marker recognition, it is advisable to place the camera directly above the work area. In this case, the optical axis should coincide with the normal vector to the surface of the latter. Such configuration minimizes the marker overlap by components of the 3-axis chassis and simplifies the camera calibration procedure. Based on the geometric dimensions of the 3-axis chassis, it is necessary to select the parameters of camera lens, allowing seeing the entire work area in one frame. The main parameter in this case is the height of camera placement. Knowing it, it is possible to determine the lens' Angle of View (AOV) by using (1):

$$\alpha_v = 2\arctan\frac{S}{2h}, \tag{1}$$

where $\alpha_v$ is AOV of the lens, $S$ is the size of the work area, $h$ is the distance between the camera and the work area.

Once the location and parameters of the optical system are determined, it is possible to proceed to camera calibration. The ArUco library includes all the necessary tools for carrying out this process. The camera calibration procedure consists of the following steps. Firstly, a marker size is selected in bits as well as the size of a dictionary. The minimum marker size is 4x4 bits; a dictionary can contain a minimum of 50 different markers. Then, in accordance with the selected marker type and dictionary, the corresponding calibration table is generated, which is a field of a specific size, where markers are placed. The number of markers is determined experimentally; their size can be arbitrary and differ from the final size, which will be used directly for recognition. The latter is caused by the fact that the calibration table is needed only for obtaining parameters of the optical system. The ArUco library implements two main types of calibration tables: a table consisting only of ArUco markers and a table representing a checkerboard pattern where, in its white cells, ArUco markers are placed (this calibration method is called ChArUco). After creating the calibration table, an array of its images from different angles is obtained. All images should vary as much as possible, and the more images there are, the more accurate the calibration will be. It should be noted that the advantage of the calibration method with the ChArUco table is that, while obtaining a set of images, occlusions and partial views, when the table may not completely fall into the frame, are also acceptable.

### C. Accuracy Evaluation

Undoubtedly, the positioning accuracy depends on the camera resolution. To calculate the theoretical resolution of a camera, which directly affects the accuracy of determining the optical marker position, the following equation is used (2):

$$C_r = N\frac{S}{C_s}, \tag{2}$$

where $C_r$ is a camera resolution in mm, $S$ is the size of a work area in mm, $C_s$ is a camera resilution in px, $N$ is the Nyquist factor, which value must be 2 or more according to the Nyquist-Shannon Signal Sampling Theorem.

However, this statement is true only if machine vision is the only way to determine the size of objects in a frame, while in the system under consideration there is an additional method of measurement. Optical markers are located on a moving carriage of a 3-axis chassis, controlled by servo-step drives. Each drive is equipped with an incremental encoder capable of determining the relative displacement value with a given accuracy. Thus, knowing the physical accuracy of the camera and the resolution of the incremental encoder, the maximum interpolation coefficient can be obtained as (3):

$$k = \frac{C_r}{E_r}, \tag{3}$$

where $C_r$ is a camera resolution in mm, $E_r$ is an incremental encoder resolution in mm.

The proposed approach will allow determining the size of objects in a frame with subpixel accuracy. In this case, it will be possible to assume that 1 pixel of an enlarged image corresponds to the resolution of the encoder, and errors in finding the exact position will be determined by the accuracy of the interpolation algorithm.

## V. Results

In the experimental installation, camera height is set to $400\,\mathrm{mm}$, work field size is $500\,\mathrm{mm} \times 500\,\mathrm{mm}$. Therefore, based on the (1), the angle of view equals 65°. A Withrobot oCam-5CRO-UM camera (OmniVision OV5640 CMOS Image Sensor, max resolution $2592 \times 1944$) and a Withrobot 3018PL002 lens (focal length $(3.00 \pm 0.15)\,\mathrm{mm}$, relative aperture $1.8 \pm 5\%$, Angle of View $65° \times 111° \times 126°$ $(V \times H \times D)$ with $1/2.9$" sensor size) were used during experiments.

During tests, a computer with the following configuration was used: 6-core AMD Ryzen 5 2600 3.3 GHz, 16 GB RAM DDR4 3000 MHz, Gigabyte GeForce GTX 1070 Ti, Windows 10 Pro x64. The Python 3.8.1 programming language and the OpenCV 4.1.2 library were used for the software implementation. According to developers' recommendations, the calibration process was performed using a ChArUco board (Figure 4) with $6 \times 6$ markers. The size of a calibration table is $200\,\mathrm{mm} \times 300\,\mathrm{mm}$, with 7 columns and 5 rows. The table was made using UV printing on a white foam-core. In the experimental installation, Leadshine CS-D1008 servo-step drives were used, which made it possible to obtain a resolution of 12.5 μm for all axes.

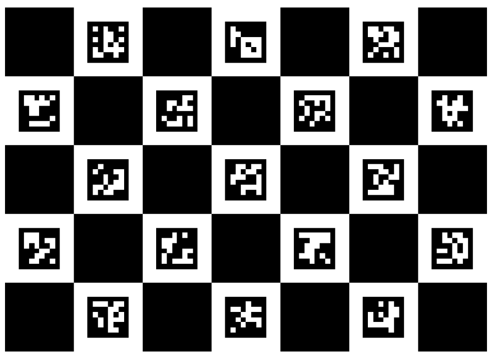

Fig. 4. ChArUco board.

After performing the calibration using (2) and (3), the camera resolution ($C_r = 0.51\,\text{mm}$) and the maximum interpolation coefficient ($k = 40.8$) were calculated. However, it should be noted that the system that determines the position of a module on a carriage suspension may have lower positioning accuracy than the system located on a suspension itself (the accuracy of which must be a priori equal to or greater than the resolution of servo encoders). This happens due to the fact that the procedure of determining the maximum size of the processing area and starting point coordinates of a tool was previously carried out manually with accuracy being within 0.1 mm. It is evident that such precision is sufficient enough to solve the given task. Based on the foregoing description, the interpolation coefficient was taken to be equal to 4, which gave the resolution after bicubic interpolation as $10368 \times 7776$, and $C_r = 0.1275\,\text{mm}$. Using a test computer with libraries, mentioned above, the speed of processing one image frame from the camera (together with interpolation) takes app. $130\,\text{ms}$, which can be considered a sufficient result for the recognition task being solved statically. An example of recognized markers is shown in Figure 5.

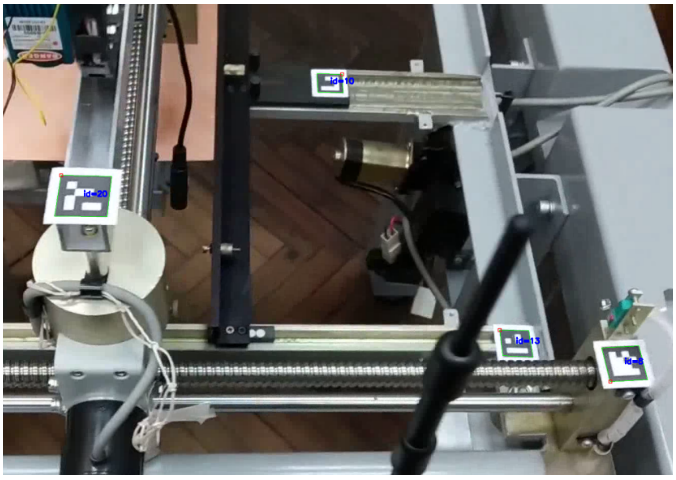

Fig. 5. An example of recognized markers.

To sum up, the following initialization algorithm for a new module was implemented based on the conducted experiments:

1) An operator installs a module on the carriage suspension, turns on its magnetic mount, turns on the power supply and the safety line [9], and then turns on the general power supply of the installation.
2) The control system accesses the machine vision module to obtain a preliminary configuration of the workspace.
3) The machine vision module takes an image from the camera in a normal (without interpolation) resolution, this image determines the dimensions of the work area, security zone, suspension coordinates, dimensions and location of the module (on the left or right mount), as well as the position of the point that will be taken as a preliminary machine zero. All the obtained data is transmitted to the control system. The accuracy at this stage is $\pm 1\,\text{mm}$ (similar accuracy is inherent in mechanical limit switches).
4) The control system begins to move the carriage to the zero position, considering its location and positioning accuracy at this stage ($\pm 1\,\text{mm}$).
5) Having reached the zero position, the control system resets the coordinates obtained from incremental encoders and starts moving the carriage to the maximum coordinate.
6) After reaching the maximum coordinate of the axes, the control system memorizes the values obtained from encoders. These values will be the maximum size of the work area with accuracy being equal to accuracy of the encoder (12.5 µm in this case).
7) At this point, the homing procedure is considered complete. The control system returns the carriage to the center of the work area and relinquishes control to the machine vision module.
8) The machine vision module takes a series of images, shifting the carriage along the axes and remembering the exact coordinate values received from encoders.
9) Based on the obtained series of images, the interpolated image with markers is obtained. It determines the exact coordinate of the tool axis with respect to machine coordinate system. Machine zero is shifted to this coordinate.
10) Geometric parameters of the chassis and the installed module are considered fully defined and the control system proceeds to the main program cycle.

## VI. Discussion and Future Work

Methods of machine vision make it possible to accurately determine distances on a plane. However, for the full-fledged operation of modules in three-dimensional space, it is additionally required to determine the distance from a tool base point to a processing plane. At the moment, the problem is successfully solved by using the point triangulation method. This approach is most widely used when building 3D scanners, which accuracy can reach several micrometers. However, the described approach requires at least two cameras with a predetermined location. Contrast lighting is also often required. Therefore, at the current stage of development, a decision was made to additionally include a probe in a module, which needs precise height positioning, to accurately set it relative to the processing plane. Currently, a contact sensor mounted directly in the work area is used for experiments. To set the Z-axis value to zero, the carriage drives up to the point where the sensor is located and goes down to touch a probe or tool.

The optimal size of ArUco markers has been experimentally determined. For the considered chassis with a working area of $500\,\text{mm} \times 500\,\text{mm}$, $25\,\text{mm} \times 25\,\text{mm}$ markers are used. However, as noted in Section 1, the concept of a modular platform suggests using a chassis line of different sizes. It is undeniable that for a chassis with a large work area, the camera height will be different, and therefore the optics too. As a result, it is necessary to identify a relation that, when knowing the size of a work area and a camera height, can determine the optimal marker size, which allows achieving a positioning accuracy not lower than in the experimental setup.

It should also be noted that optical markers can become dirty when equipment is in operation. The maintenance schedule should describe the procedure of marker cleaning. This operation is not technically complicated and is usually performed by staff with a low-skilled labor.

In machine vision systems, where high-precision object location is required (3D scanning, automated high-speed robotic lines, etc.), special shadowless light sources are used, which, depending on their configuration, allow better recognition of the object contours or its volume. The proposed approach is based on the use of augmented reality tools that were originally designed to work in adverse lighting conditions. Therefore, at the current stage of development, diffuse LED lamps are used to illuminate the work area, and the selection of specialized light sources is considered inadvisable.

Changing the method of mounting modules on a carriage suspension made it possible to use two modules simultaneously. However, it is not currently implemented in the software. In the future, it is planned to add this feature to obtain hybrid devices that work with two modules simultaneously. However, it will also be necessary to further divide modules into classes according to the principle of processing (measuring) compatibility.

Since all components in a modular 3-axis platform, as well as instrumental equipment, are provided with coordinate markers, known by the system, it is possible to use external augmented reality tools. In particular, it is planned to create an application for mobile devices and augmented reality glasses. Such system will allow creating interactive manuals for modules installation and configuration, visualizing the machining process (for example, to create an animation of a cutting tool movement, or as a visual progress indicator for three-dimensional printing), as well as displaying additional information about the machining or measuring process (for example, three-dimensional heat map for a coordinate measuring machine or sensors readings).

## VII. Conclusion

In conditions of increasing the flexibility of production equipment, a carefully thought-out technology for securing interchangeable modules plays an important role, and helps minimizing the operator's efforts to install, fix and calibrate interchangeable devices on a 3-axis platform. The current stage of an experimental modular platform development is focused on methods of equipment reconfiguration with the possibility of its automatic preparation for operation.

In the paper, a novel method for plug-in module installation on a 3-axis platform carriage, which uses a machine vision system for a subsequent tool registration and calibration, is proposed. As an input to the system, a set of labels is used, located directly on the plug-in module and processing head, and on the desktop, which allows calculating the relative positions of the module, carriage, and work area relative to each other. The calculation accuracy, undoubtedly, depends on both the accuracy of camera mount and on the resolution of a frame. As a mounting method, it is suggested to use electromagnets located on a platform suspension and providing a clamping force sufficient for the module to perform its direct functions without changing its location. In the future, it is planned to develop this approach and conduct a series of experiments with various types of equipment.

## Acknowledgment

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