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PASSIVE COMPLIANCE AND COMPUTER VISION TECHNIQUES FOR PRECISION IMPROVEMENT OF ELEMENT PLACEMENT OF ROBOTIC-BASED BRICKLAYING

István Vidovszky
Budapest University of Technology and Economics (BME), Budapest, Hungary

Abstract

Besides robotic-based manufacturing in the prefabrication of the construction elements, on-site robotic-based construction technologies also tend to increase their relevance. In the case of such construction tasks, e.g. automated bricklaying, that involve robotic element placement activities, the precision of the placement of the elements by robotic actuators is influenced by many technical factors, among which the material picking from palettes is one of the determining ones. Any dislocation during the pallet building or at the picking process is inherited by the further phases unless some measurements are taken either for the elimination of the failure or the readjustment of the position of the element. For this purpose, in the classical periods of robotics, passive compliance methods, namely physically aligning elements and surface forming were applied at the various technological steps. In the present day, computer vision-based techniques can be applied as well. In the frame of this research, a comparison of passive compliance methods and computer vision techniques is made in robotic material picking of small-scale construction elements. As far as both methods have pros and cons, a highlighting of the advantages and disadvantages of the various solutions in case of various circumstances was executed.

Keywords: automated bricklaying, robotic construction, pick and placement, passive compliance, computer vision

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1. Introduction

Beyond the technology-related questions, the typical fields of challenges in construction automation are the elimination of environmental circumstances to assure accuracy and quality [1], the temporal harmonization of the processes such as the material transport and handling for undisturbed workflow, the handling of the relatively large weights of construction and the assurance of safety of the human workforce who are present on the site [2].

Robot-Oriented Design (ROD) is a fundamental approach to the design and implementation of robotic technologies, the principles of which allow for an understanding of the elements to be taken into account in order to achieve an efficient result during robotic construction. The concept of ROD in the construction industry dates back to 1988 when the basic principles of this approach were defined [3]. Later, following these principles, many robotics-based construction technology-related research concepts were analyzed in several works [1,4,5,6,7]. There were already conceptions about automated material handling as part of the organization of an automated building construction system in the 1990s [8]. In the construction industry, ROD influences the entire construction process from material procurement through the organization of automated construction sites to the development of building elements and processes, thus it also plays an important role in the pick and placement activities [1,3]. Material handling and pick and placement tasks are part of the challenges that ROD has to face. The classical passive compliance techniques can be used for precision control in these fields.

Corresponding author email address: vidovszky.istvan@epk.bme.hu

Sensors have been tested for a long time for various purposes (mainly for navigation and positioning) in the work of construction robots [9,10]. According to some opinions, sensors for material settings are indispensable [11]. Sensors are more expensive than passive compliances, and in some cases, weather effects (wind, humidity, dust, etc.) can cause uncertainty of perception on a construction site by hindering the sensing, even though sensors are generally useful to make the system more reliable, and for material picking computer vision method looks the most beneficial.

The use of computer vision for pick-and-placement tasks, which among the external sensors forms a distinguished option, has been applied for a longer time too. Attempts were made as early as the end of the 1980s [12], and several research has been dealing with the topic up to now [13,14,15,16,17,18]. There are also some construction-industry-focused analyses related to this topic [19,20,21,22,23]. The application of sensors for various purposes of automated construction, involving the possible use of computer vision is analyzed by Vähä et al. [20]. Some attempt to apply computer vision for picking up categorized waste types on the construction site is also known [21,22]. There are some recent research papers on computer vision techniques for palletizing, among which appears a cement bag palletizing problem too [23].

In this paper, some further aspects of the above-mentioned fields are analyzed.

2. Methodology

In the case of material feed, there are many unsolved issues, which form limits regarding to autonomy of the automated construction technologies. In the case of a robotic system that handles solid construction elements, palletizing, and positioning of the elements are critical initiation actions of the placement. Improper grabbing of the element will cause inaccurate placement and, consequently, inadequate construction. For this reason, automated construction systems need element positioning control. In the case of material handling and palletizing two kinds of solution can be distinguished: the classical passive compliance method and the handling of the dislocation with an external sensor system.

After a few preliminary experiences [24,25], in the frame of this investigation, a series of laboratory experiments were conducted to test both the passive compliance methods and the option of computer vision-based picking of the construction elements, and the experiences of pick and placement tasks connected to building simple brick walls are evaluated in this paper.

For the pick and placement task, model bricks, 3D printed aligning templates, a Dobot Magician 4DOF robotic arm, and model bricks were used. For computer vision, a laboratory computer vision system (Dobot Vision Studio software, Dobot Magician 4DOF robotic arm, and Hikvision MV-CE050-30VC industrial camera) was applied.

2.1. Aiding the material handling with passive compliance techniques

In the case of passive compliance, an eventual minimal offset (under measurement tolerance) can be handled by the classical methods of robot-oriented design, like inclining positioning surfaces (*Fig. 1*) or positioning pegs and holes (*Fig. 2*) at the seizing, and at the placement of the elements [1,3,26,27]. These methods can eliminate eventual offsets that turned up during the preceeding phases of the execution.

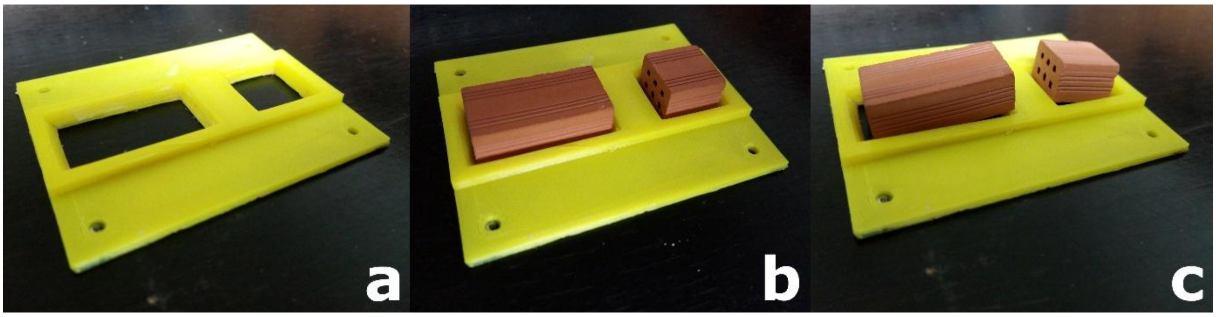

Fig.1 Passive compliance with aligning templates: a) aligning template b) precisely placed elements c) offsets above the manageable limits

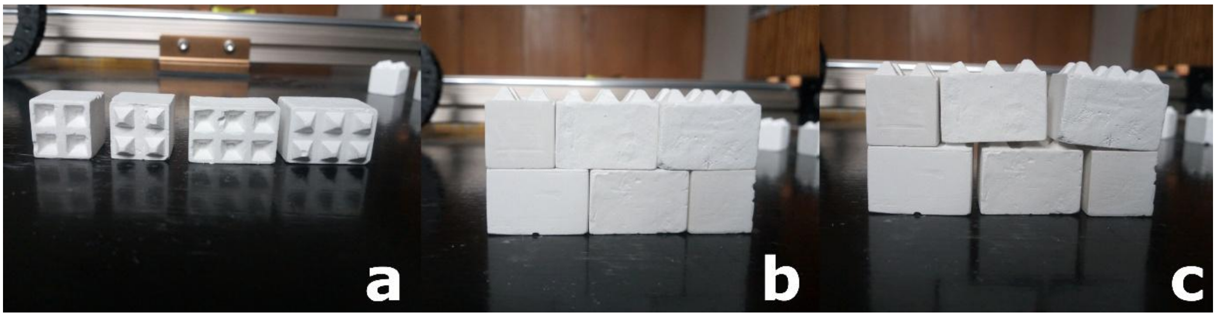

Fig.2 Passive compliance with positioning pegs and holes (tenons and mortises): a) the used elements b) precisely placed elements c) offsets above the manageable limits

2.2. Aiding the material handling with external sensor systems

Eventual offsets that turn up while removing items from pallets or while filling up the pallets can be eliminated with external sensors at the seizing or at the placement, which are not part of the kinetic body of the robot. These sensors can be installed, e.g. at the location of the picking or the placement to align the end-effector precisely on the elements to move [1,24].

External sensor systems are more expensive than the means of passive compliance and require further control as well, however, they provide steadier work and can give valuable feedback too. In the cases of picking and placing construction elements, various kinds of external sensors (e.g. ultrasonic, infrared, photoelectric, camera sensors, etc.) can be connected to the robotic system to ensure the accuracy of the seizing and the placements.

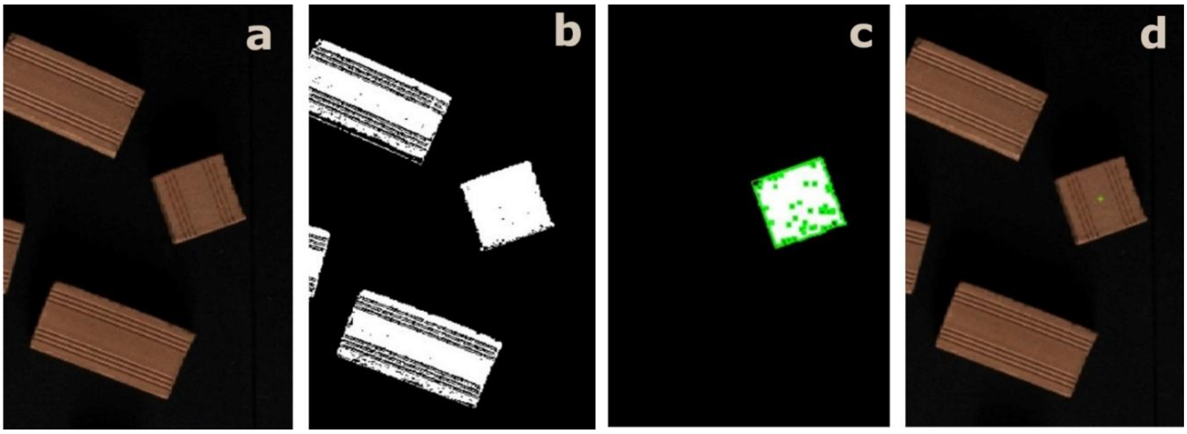

Fig.3 Computer vision-based location detection of a construction element before placement in a laboratory environment: (a) photo, (b) object detection (recognition), (c) shape mark out, (d) location of the center (reference) point.

In our experiments, computer vision-based seizing of the pick and placement tasks of solid construction elements was tested (*Fig. 3)*. In the testing environment, the pictures were captured from the camera views of the Dobot Vision Studio.

In this case, object detection is taken as a first step to identify the edges of the element. The next step is a mark-out function that distinguishes the shape from its background (*Fig. 3b*). Once the camera recognizes the contours of the object (*Fig. 3c*) a middle point (reference point) can be determined as well (*Fig. 3d*). By moving a gripper head to the position of the recognized element a perfect calibration of the camera and the physical setting is required. Besides the calibration, the RGB code ranges of the colors to be perceived are required for the software to distinguish the objects from their background. Pick-and-placement tasks were tested in the case of natural and artificial light conditions.

3. Discussion

In the present paper, analyses were made regarding material feed and element placement. Passive compliances such as aligning templates or positioning pegs and holes, according to the classical approach of robot-oriented design, make the system accurate. As a further step, the option of computer vision was tested as a method for picking and positioning control.

3.1. Evaluation of passive compliance methods

3.1.1. Analyzing the options for adjustment

Passive compliance methods were executed in two ways. In the first case, the passive alignment was applied before placement, in the other case it was executed at the placement.

- *Adjustment before placement*

Passive compliance methods can be executed before the placement, at palletizing, but in this case, any displacement or inaccuracy of the pallet mark out is inherited to all elements. It can also be applied between the picking from the pallet and the placement with an extra step by applying a positioning template (*Fig. 1*), that corrects the eventual offsetting of the alignment. The limit of the placement correction is determined by the size and the exact form of the template.

- *Adjustment at the placement*

Adjustment at the placement can be performed by aligning pegs and corresponding holes (e.g., on the top and the bottom of the elements) (*Fig. 2*). In this case, the alignment is performed automatically at the placement of the elements, correcting omnidirectional offsetting in the horizontal plane. The limit of this placement correction depends on the geometry of the elements.

3.1.2. Maximal tolerances in the case of the passive compliance methods

Regarding offset three cases can be distinguished: shifting by a vector, rotation by an angle, or the combination of the two. The maximum tolerable offset should be considered in the following three cases:

- *Horizontal shifting occurs as dislocation*

In the case of shifting, the maximum tolerable dislocation depends on the geometry of the lifted elements and the aligning template. The maximum tolerable dislocation in each direction should be smaller, than the horizontal projection of the length of the inclining surface (*Fig. 4b*) or the aligning pegs (*Fig. 5b*) in each direction, and the tolerated maximum shifting (d_{max}) can be smaller than the resulting vector of d_{1max} and $d_{2\,max}$.

$$d_{max} < \sqrt{d_{1\,max}^2 + d_{2\,max}^2}$$

- *Horizontal rotation occurs as dislocation*

In the case of rotation, the maximum tolerable angle of dislocation is also depending on the geometry of the aligning template and the lifted elements (*Fig. 4c*) (*Fig. 5c*) the maximum rotation $\boldsymbol{\varphi}$max should be smaller than the smaller angle of the maximum possible rotations ($\boldsymbol{\varphi}$1max and $\boldsymbol{\varphi}$2max), in which cases the edges of the element would touch the outer rims of the templates on either side. The absolute maximum tolerable rotation is calculated by the following steps (*Fig. 4e-f*) in the case of aligning template:

$$\alpha = sin^{-1}\frac{b+2b'}{\sqrt{a^2+b^2}}\ ;\ \beta = sin^{-1}\frac{a+2a'}{\sqrt{a^2+b^2}}\ ;\ \sigma_1 = tan^{-1}\frac{b}{a};\ \sigma_2 = tan^{-1}\frac{a}{b}$$

$$\varphi_{1\,max} = \alpha - \sigma_1;\quad \varphi_{2\,max} = \beta - \sigma_2$$

$$\varphi_{max} < min\,\{\varphi_{1\,max};\ \varphi_{2\,max}\}$$

In the case of aligning pegs (*Fig. 5c*), it is calculated in the following way in the case of the given geometry (*Fig. 5e*):

$$\gamma = sin^{-1}\frac{e''}{\sqrt{2(e+e")^2}}\ ;\ \sigma_3 = 45°$$

$$\varphi_{max} < \varphi_{3\,max},;\ \varphi_{3\,max} = \gamma - \sigma_3$$

- *A combination of rotation and shifting occurs*

In the complex case when both rotation and shifting occur at the same time, the maximum rotation is calculated similar way, as it was demonstrated in point b), but at the calculation of the *a+2a'*, *b+2b'*, or *e+e"* segment each should be shortened by the component of the shifting vector that is parallel with the correspondant side ($d_{a\parallel}$; $d_{b\parallel}$; $d_{e\parallel}$). In the average case, if *a*>*b*, then $\boldsymbol{\varphi}_{1max}$ will be the smaller and determining angle of the maximum tolerable rotation, in cases if the correspondent component of the shifting vectors correspondent component is larger than the difference between the two sides, the smallest tolerable rotation angle might be defined by $\boldsymbol{\varphi}_{2max}$.

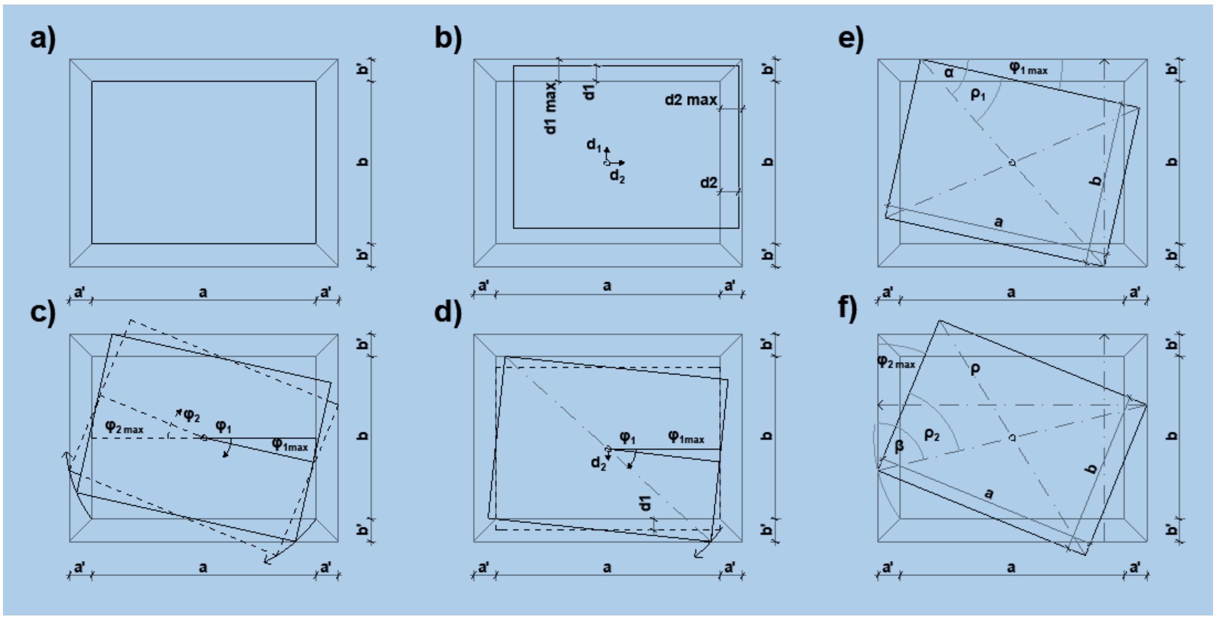

Fig.4 Maximal offset tolerances in the case of the alignment template: (a) element in the aligning template, (b) shifting, (c) rotation, (d) rotation and shifting (e-f) calculation of the maximal angles

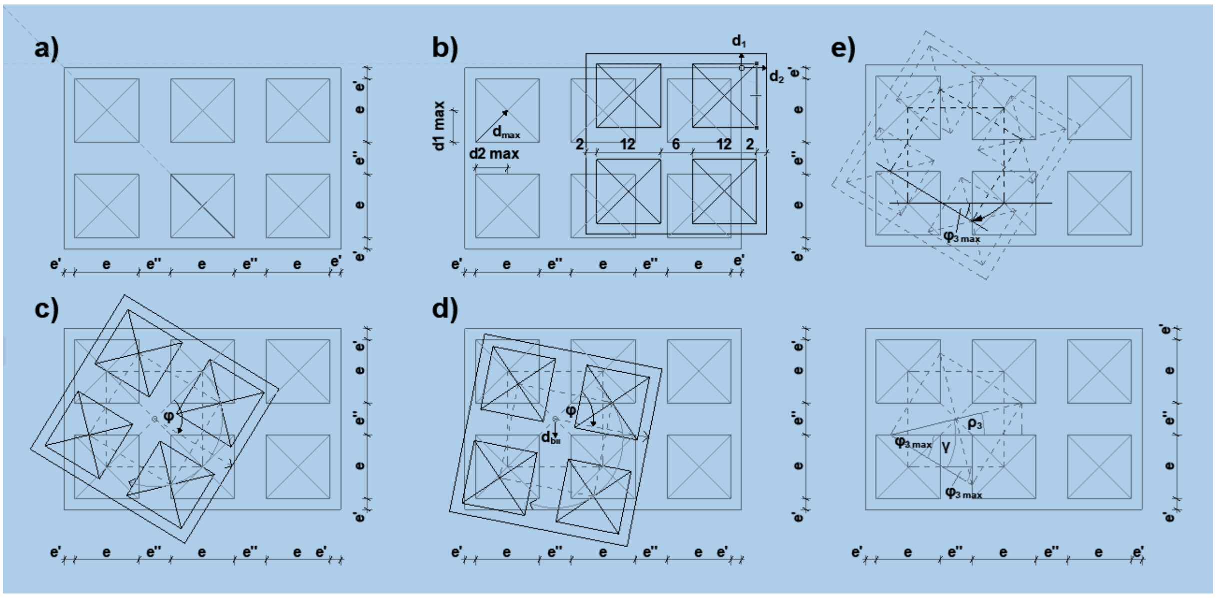

Fig.5 Maximal offset tolerances in the case of the alignment template: (a) element in the aligning template, (b) shifting, (c) rotation, (d) rotation and shifting (e) calculation of the maximal angles

To the passive compliance methods, a few comments also have to be made:

- As far as a 4DOF robotic arm was used, rotation related to the horizontal plane did not occur in the analyzed cases. The applied parallel gripper cannot be tilted, its fingers are assumed to be vertical and the manipulation surface is theoretically horizontal.
- In the analyzed case of the unit equipped with pegs and holes, the lengths of the sides of the aligning pegs are equal, which results in 45° in the case of the angle σ_3. It is typical of similar construction elements because this geometry enables the joining of the elements perpendicularly to the wall too, but other cases are also conceivable.

3.2. Evaluation of computer vision method

In the case of the computer vision method (*Fig. 3*), the alignment before seizing is performed by the computer, and there is no need for the specific shape of the elements, which is an advantage from the point of view of the cost. There is no need for further adjustment or sensor-based control between picking from the pallet and the placement, so it can be executed directly, which is an advantage of time.

In the case of artificial light, the processes were running without a problem, but in the case of natural light, various failures occurred. On the one hand, in consequence of the changing contrast between the color of the element and the background in some cases, inadequate boundary identification and as a consequence of it, inadequate definition of the center of the seizing could be observed. On the other hand, regarding the colors, frequent re-setting was required of the RGB color domain, as a consequence of the change in the lighting conditions.

4. Conclusions

Passive compliance is the traditional method of robot-oriented design and still has many advantages today, despite the fact that solutions based on it have easily identifiable limitations. In this paper, these geometrical limits were presented in two analyzed cases. As a general critique of the results of the analyses, it has to be stated that the geometry of physical objects is never perfect, consequently, the maximum tolerance in reality is always less than the ones in theory. Apart from this, by the analogy of this study, further situations with different geometry can be analyzed in the future.

In contrast to the other two discussed methods, in the case of the computer vision method, precision is not the main problem. As far as the proper calibration of the camera to the physical environment results in satisfactory precision, even scattered construction elements can be grabbed in the perfect position if the color setting covers the required range in the case of the given light conditions. However, it was experienced during the tests that a change in visibility, e.g., the change in the perceived shade of color of the construction elements as a consequence of the changing light conditions, can affect the working of the computer vision-based system. For this reason, during the application of the technology, the light conditions have to be stabilized, or the development of dynamic light adaptation is required.

Finally, *Table 1* summarizes the comparison of the different methods.

Table 1. Precision control methods

Method	**Passive compliance methods**		**Computer vision method**
	adjustment before placement	**adjustment at the placement**	
Applied implements	• the use of an aligning template applied between the picking from the pallet and the placement	• aligning tenons and holes are applied to the elements	• recognition and aligning with the help of a camera
Advantages	• low cost • the form of the elements do not have to be specific • the color of the elements is indifferent • reliable in case of various light circumstances	• low cost the color of the elements is indifferent • reliable in case of various light circumstances	• applicable for scattered elements as well • the form of the elements is indifferent
Disadvantages	• an extra step has to be taken before placement • the offsets can be corrected only in the scale of the template	• offsets can be corrected only in the scale of the tenon • the element’s form is specific • elements are more vulnerable	• the light conditions are influencing the operation • the background has to be visually differentiated from the elements

In this research, the problem was tested only in model scale and laboratory environment. For the further evaluation of the here investigated problem in the case of a real construction environment an analysis of the real scaled execution should be conducted.

5. Summary

In the case of automated material feed and element placement, passive compliance methods are basic solutions of robot-oriented design, however, in our time more and more often sensor-based alignments are applied too. Computer vision-based solution, which was also analyzed in the present study, could solve further problems and it seems to become the future way of improving alignment precision, but even though it has a promising future, some issues still must be solved before it can be considered as perfectly reliable solution for on-site construction technologies. For further development, more revealing research on this topic could be a possible continuation of the present one.

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