The way to expand the operation area for robot manipulators to increase flexibility of process lines

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Abstract. The issues of increasing flexibility of process lines due to optimizing the mechanical components of cyber-physical production systems in which small-size industrial robots are used have been encompassed. The approach to expanding operation areas for industrial robot manipulators is one of the most difficult ones in practical implementation, but it has a number of advantages in terms of increasing the technological flexibility of robotized lines. Expanding the operation area for a manipulator is possible through several ways, for instance, by increasing the linear sizes of links, by giving an additional degree of freedom – through installation of a self-propelled base or mounting of such manipulator on a railtrack. However, the studied methods have considerable deficiencies one of which is a high cost of such solutions. The method to expand the manipulator operation area was offered, which provides for relocation of the manipulator to fixed base surfaces. The requirements for the manipulator relocation mechanisms have been analyzed. A specific embodiment of the mechanical part of the relocation mechanism drive adjusted for the performance features, in particular, for ensuring force pressing to the base surfaces for their reliable coupling, has been suggested.

1. Introduction

The global market of robotics is continuously developing and transforming [1,2]. However, robotization of industrial, microelectronic and automotive industries is considered to have reached its limit. Such industries are distinctively characterized with a relatively strict orientation to a specific production process. If such production process has to be changed, it is quite often necessary to carry out works on re-adjustment and re-arrangement of equipment, which significantly reduces the flexibility of such facilities. Currently robotization is more and more required for process lines in small enterprises, laboratories and industries with wide ranges of products and low series of production [3,4]. Such industries usually compensate for limited technological flexibility and restrictions in the existing automation systems actually by using manual labour. A significant deterrent to distributing robots in small enterprises is also relative complexity of maintenance and control of such process lines, as well as the cost of commissioning and payback periods of robotization [5]. Therefore, for small enterprises (laboratories etc.) with wide ranges of manufactured products released in small batches it is necessary to increase flexibility of automated lines and to reduce their prime cost.

It should be noted that if these objectives are considered from the most general standpoints, the improvement of mechanical components of the cyber-physical system will make it possible to increase the level of integration of computing resources into the production process of the industry. In turn, it will result in a possibility to extend the range of manufactured products without increase in the prime cost associated with re-adjustment of process lines.
2. Methods to expand the operation area of manipulators

Small-size industrial robots which are quite widely used in various production processes usually have compact dimensions and thus relatively small operation areas. In the common case, the manipulator’s base is rigidly fixed (Figure 1), and the technological transport with component parts move relative to it (Figure 2). The enterprises manufacturing small-size products (e.g., devices) by using process lines equipped with manipulators use the general robotized operating surface on a relatively large area of distributing the product components being assembled. At the same time, the robotized operation area is normally divided into fragments which are rather distant from each other. Workstations designed for a particular process cycle operation are equipped with robots, and the connection between them is arranged by using conveyor-type technological transport (flow line) [6].

![Figure 1. Method of robot placement and its operation area in horizontal projection.](image1)

![Figure 2. Fragment of a robotized process line with several workstations.](image2)
lines, if workstations are covered by a common operation area of the manipulator, which will make it possible to refuse not only from additional manipulators, but also, in a perfect case, from the technological transport. Several basic methods to expand the manipulator operation area are known, and one of them is increasing linear dimensions of the manipulator links (Figure 3).

![Figure 3](image.png)

**Figure 3.** Expanding the manipulator operation area through increasing the linear dimensions of the manipulator links and its operation area.

This method has a number of significant disadvantages: to ensure the required precision, it is necessary to increase rigidity of all manipulator elements, which, in turn, results in an increased mass of mobile parts and inertion moments, increased loads on hinge gearboxes, necessity to improve the positioning accuracy, which considerably increases the manufacturing requirements. The power capacity of the electromechanical part of the manipulator also has to be enhanced. Additionally, positioning errors considerably grow, and they should be reduced, in particular, through calibration [7-12]. Compensation of such features leads to a considerable (disproportionate) growth of the robot cost, which makes it impossible to practice such approach for most of industrial problems. The second basic method for expanding the manipulator operation area is giving an additional degree of freedom – for instance, a self-propelled base on a flat surface or base installation on a railtrack (Figure 4). This method to expand the manipulator operation area has the following basic disadvantages: it is necessary to prepare a special transportation surface or a railtrack, a rather complex base position detection system is needed, and mobile or autonomous power supply systems are necessary. In such case, the cost of such robotized system is significantly incremented, which considerably restricts the possibilities to use such method to increase process flexibility.
3. Suggested method of manipulator relocation to base surfaces

One of the variants to expand the manipulator operation area, which is free of the main disadvantages of the two above methods is the method of manipulator relocation to fixed base surfaces (Figure 5).

This method provides for the following. The manipulator is placed on a repositionable base which is mounted on specially prepared rigid base surfaces, and which ensure a definite spatial position of the
manipulator. The mechanism providing manipulator relocation can have a relatively simple structure not requiring a complex positioning system. It should be noted that in addition to the function of relocating the manipulator base to the required area, the mechanism should reliably fix the base on the basic points (the embodiment example will be discussed further). The manipulator can be relocated both by the radial pattern and by other patterns depending on a specific structural solution of the repositioning mechanism. The suggested method to expand the manipulator operation area which is being discussed has the following advantages:

- a relatively simple repositioning mechanism not requiring high positioning precision;
- the initial manipulator positioning precision is preserved;
- no additional calibration of the manipulator is needed;
- no mobile power system is needed;
- increased process flexibility with simultaneously reduced prime cost of the automated line.

4. Implementation of the suggested method for manipulator relocation to base surfaces

Let us consider the main specific features in implementation of the radial pattern to relocate the robot manipulator to base surfaces. To dismantle and install the manipulator on the base surfaces, the vertical lift angle of the relocation mechanism will be sufficient within the range of 5-10° (Figure 6).

For precise positioning on the base surfaces, the hinges of the relocation mechanism holding the mobile base on which the mating base surfaces and the manipulator itself are fixed, should have compliance (elastic hinges) which will compensate for both positioning errors and the errors in location of the fixed base surfaces.

An important condition for reliable basement is also creation of forced clamping of the mobile base to the base surfaces (when coupled) by the relocation mechanism. This condition is predetermined by ensuring a high coupling rigidity adjusted for the weight of the mobile parts of the manipulator and
dynamic loads conveyed to the base surfaces during the operation of the manipulator. Based on the considered requirements, a mechanism ensuring the lift and relocation by a mobile support is suggested. The distinctive feature of this mechanism is using the lever transmission between the electrical engine and the levers of the relocation mechanism. In contrast to the conventional mechanisms used in drive solutions – for instance, fluvial and screw-type, the suggested four-link mechanism has a variable transfer function which makes it possible to provide forced clamping without increasing the momentum developed by the electric engine.

The mechanism consists of two levers coupled between each other with a piston rod. Figure 7 shows the drawing of the four-link mechanism and its operation in several phases; where a is the shoulder of the first lever, c is the shoulder of the second lever, d is the distance between the rotation levers of the axes, and b is the distance between the hinges of the piston rod.

![Figure 7](image)

**Figure 7.** Mechanism operation phases: 1-1 position 0° (clamped to base surfaces); 2-2 intermediate position; 3-3 position 10° (raised).

The first lever is connected with the electric engine or intermediate reducer, the second one – with the output lever of the relocation mechanism. The levers stand on the bearing supports, the piston rod is connected to the levers by means of fingers installed on the bearings. The mutual disposition of the rotation axes of the levers, the ratio between the lengths of the levers and piston rod are selected so as to ensure the turning angle of the second lever equal to 10° during the mechanism operation, at the same time, the first lever will make a partial turn.

The nature of change of the obtained gear ratio in such mechanism is shown on Figure 8. As we can see, in the position 0° (clamped to the base surfaces), the mechanism has the maximum gear ratio and thus the generated force which gradually decreases as the second lever returns, and somewhat increases when the second lever is put into the position 10° (raised), at the same time, the minimum value of the gear ratio stays within the range of 10...12.

![Figure 8](image)

**Figure 8.** Gear ratio of the i – four link mechanism from the turning angle of the output lever.
The function of the turning angle $\beta$ depends on the initial angle $\alpha$, and looks as follows: $\beta(\alpha) = \arccos \lambda + \arccos \varphi$, in the range $0^\circ < \alpha \leq 180^\circ$, thereat:

$$\lambda = \frac{d - a \cos \alpha}{\sqrt{a^2 + d^2 - 2ad\cos \alpha}}$$  \hspace{1cm} (1)

$$\varphi = \frac{a^2 + c^2 + d^2 - b^2 - 2ad\cos \alpha}{2c\sqrt{a^2 + d^2 - 2ad\cos \alpha}}$$  \hspace{1cm} (2)

b) $\beta(\alpha) = \arccos \varphi - \arccos \lambda$, in the range $180^\circ < \alpha \leq 360^\circ$, where $\varphi$ and $\lambda$ have the same dependencies.

The gear function $i(\alpha)$, as the ratio of the $\beta$ angle to the increment $\alpha$, is the first derivative from the turning angle function: $i(\alpha) = \beta(\alpha)$.

Therefore, the suggested relocation mechanism for the robot manipulator mobile base, based upon the four-link mechanism, enables us to obtain the following: strong clamping effort, high efficiency coefficient, small momentum required to start motion (breakaway) from the position $0^\circ$ to the position $10^\circ$, high resource, and structure simplicity.

5. Block-modular method for process section arrangement

Flexibility of process lines can be significantly upgraded due to creating a configurable process section (Figure 9) including an operating field and a set of process modules. The operating field is a set of base groups placed with a certain step and certainly arranged in the space.

The process modules constitute process equipment installed in a unified structural element which provides a special interface with adjacent process modules. Feeding and control, as well as control signals and service signals are transmitted to the process modules through the contact groups serving as base surfaces.

If necessary, base surfaces can be equipped with mechanical catches for the process module to be reliably held. The process modules are moved to uniformly located bases by means of a special relocation mechanism with the Cartesian reference system. Each module has its fitting assembly, transmitting assembly, and it can be turned by 90 degrees.

![Figure 9](image_url) Operating field with base groups.

The process modules can be produced in dimensions divisible by the step of the contact groups’ location, and they can be placed on several bases (Figure 10). The block-modular arrangement method enables fast (several minutes) re-configuration of the process line, which, in combination with the possibility of internal re-adjustment of the process modules, will make it possible to obtain a high level of internal flexibility. The specific variant for process line configuration for microlens assembly has been suggested.
6. Conclusions
To enhance the flexibility of process lines, a method to expand the operation area of the robot manipulator as a component of the cyber-physical system through manipulator relocation to the base guiding surfaces with fixation has been suggested. A specific method to implement the relocation mechanism has been offered, which makes it possible not only to optimize assembly operations performed on process lines, but also to simplify the robotization of process lines for production of a wide range of small-size products in small series. A method has been suggested for upgrading the flexibility of process lines through creating a configurable block-modular process section.

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