Criteria for Comparison of Robot Movement Trajectories and Manual Movements of a Doctor for Performing Maxillofacial Surgeries

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***Abstract*—In this article, in order to justify the expediency of using a robot in maxillofacial operations with a diode laser, four basic criteria for comparing typical trajectories are presented, which allow quantifying the program movements of the robot and the manual movements of the surgeon. The presented comparison criteria are in part based on the ISO 9283. An experimental setup has been developed for the research, in which the medical instrument is moved using the robot KUKA LWR 4+. The robot's movements are measured using a coordinate measuring machine, a laser tracker. Along with the measurements of the program movements of the robot, the manual movements of the surgeon are also measured.**

***Index Terms*—medical robotics, collaborative robotics, human–machine cooperative system, surgical assistants, laser tracker, trajectory evaluation, accuracy, diode laser**

I. Introduction

When developing robotic medical complexes, it is necessary to prove the possibility and prospects of using robots in certain medical operations, which is achievable through comparing robots with a surgeon. Mostly, this comparison should be quantitative, which will make it possible to clearly explain the expediency of using a robot [1]–[4]. The robot itself, with such a comparison, is perceived only as an actuating device, a means of the programmed movement (robot assistant) of a medical instrument. Both movements of the medical tool performed by a surgeon and a robot must be carried out according to typical predetermined trajectories, which are the object of comparison. Typical trajectories are usually specified depending on the medical operation being performed.

Recently, during many surgical maxillofacial operations [5]–[7], a diode laser [8]–[10] with an impulse pump driver is widely used. This medical tool allows performing cuts of different depths and widths, depending on certain laser radiation power values, pulse time, and time between pulses. These parameters are the cutting modes from the point of view of the surgeon. When using a robot for the same operation, the cutting modes are expanded because of the additional ability to control the following parameters: the velocity of the medical tool and the air gap between the laser tip and the biological tissue. The collection of data from typical trajectories, regarding the required cutting modes, makes it possible to formulate criteria according to which the comparison of the robot's program movements and the manual movements of the surgeon will take place.

In the present study, four main criteria are presented, which allow us to perform a quantitative comparison of the accuracy and the velocity of trajectory testing from the program movements of a robot and the trajectories from the manual movements of a surgeon. These criteria are in part based on the ISO 9283 standard [11]. For the study of typical trajectories, an experimental setup consisting of two parts has been developed: for measuring trajectories from manual movements of a surgeon and for measuring trajectories from program movements of a robot.

II. Experimental Setup

The experimental setup for measuring the trajectories from the program movements performed by the robot, which is presented in Fig. 1(a), includes the following equipment:

- A laser coordinate measuring machine, (1) LTD 800 laser tracker.
- A medical robotic manipulator, (2) KUKA LWR 4+.
- A robot work tool (3).

The work tool of the robot consists of a mechanical interface (4), which makes it possible to connect the holder of the optical waveguide (5) to the flange surface of the robot (6). To be able to perform measurements, a reflector (7) of the laser tracker must be installed on the mechanical interface.

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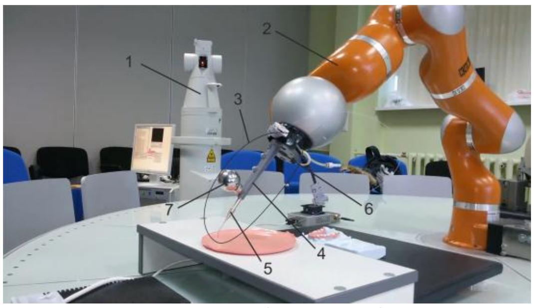
The experimental setup for measuring the trajectories from the manual movements performed by a surgeon includes the following:

- A laser coordinate measuring machine, (1) LTD 800 laser tracker.
- A surgeon's work tool (8).

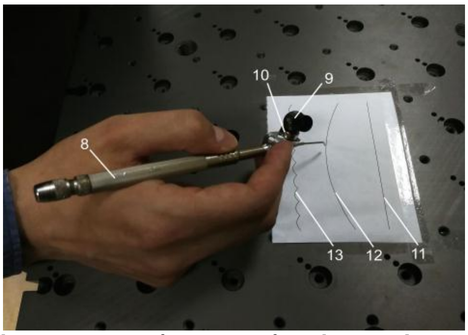
One of the main requirements for the development of a working tool for measuring manual movements was ergonomics, since the manual movements performed by a surgeon should not be limited by the excessive weight and dimensions of metrological devices, in order to obtain reliable trajectories. This is why, for measuring coordinates of points associated with the optical waveguide holder (5), it is necessary to use the laser tracker. This CMM allows measuring the coordinates of the reflector (9) having a weight that does not exceed 7 g (the reflector (7) has a weight of 170 g). In addition, the reflector is mounted on a magnetic base (10) having a weight of about 3 g. Accordingly, the total weight of the measuring device to be connected to the optical waveguide holder is about 10 g, which provides ergonomics for manual movements from the point of view of surgery. The work tool of a surgeon for measuring trajectories from manual movements is shown in Fig. 1(b).

The experimental setup allows measuring the Cartesian coordinates associated with the optical waveguide holder, both in manual movements of the surgeon and during program movements of the robot. The set of measured Cartesian coordinates forms the trajectory of the movement of the optical waveguide holder. Advantage in ergonomics from the point of view of surgery gives rise to a lack of the ability to measure the orientation of the working tool. As such, there is no need to measure the orientation, since the tolerance for the deviation of the angular position of the tool tip during the operation for both the robot and the surgeon is ±5°.

After the analysis of standard operations in the maxillofacial surgery [5, 6], a set of required typical trajectories are formed, along which the robot and the surgeon will perform the movement. Typical trajectories are linear $l_i(x_i, y_i, z_i)$ (11), semilunar $h_i(x_i, y_i, z_i)$ (12), and scalloped $f_i(x_i, y_i, z_i)$ (13) trajectories (i is the number of measured coordinates of points), which are shown in Fig. 1(b). During the experiments, an experienced surgeon conducts manual movements and also assigns program movements to the robot KUKA LWR 4+ using an intelligent system of interaction.



(a) For the measurement of trajectories from the program movements of the robot.



(b) For the measurement of trajectories from the manual movements of a surgeon

Figure 1. Experimental setup.

Obtaining the coordinates of the points of which the trajectory consists is performed by scanning the position of the reflector during its movement with a frequency of 300 Hz.

When carrying out experiments to compare the movement of the robot and the manual movements of the surgeon, instead of a biological tissue, the surface of a table (14) with minimal flatness is used to estimate the movement, and when estimating the movements performed by the robot, the table's surface is set using the program. This is necessary in order to exclude the errors from the result of the evaluation associated with the difficulties of setting trajectories and comparing them on surfaces with a complex form of biological tissue.

The experimental setup ensures that studies are carried out in accordance with the criteria for comparing trajectories presented in the following sections.

III. Criterion I: Standard Deviation of Points from Program Trajectory

The first criterion for comparing the movements of a surgeon and a robot is the standard deviation of points from the trajectory. In the example of a linear trajectory, this is the deviation of each measured point of the trajectory $l_i(x_i, y_i, z_i)$ from its projection $l_i'(x_i, y_i, z_i)$ to the midline (model) constructed using the least-squares method over all the measured points of the trajectory $l_i(x_i, y_i, z_i)$ (the standard deviation of points from the trajectory σ for manual movements has the index H and that for the robot's program movements has index R). An illustrative example, shown in Fig. 2, shows the measured points of the trajectory $l_i(x_i, y_i, z_i)$ and their projections $l_i'(x_i, y_i, z_i)$ on the midline (line), l_{pi} being the magnitude of the projection.

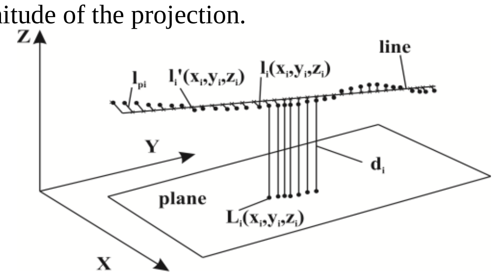
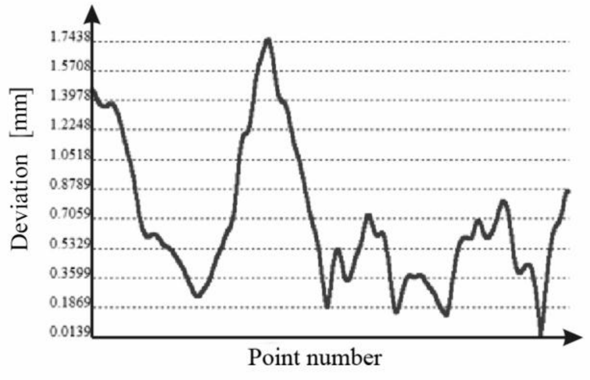
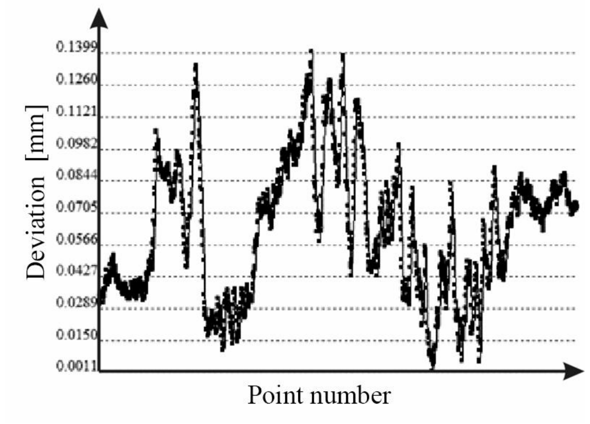


Figure 2. Visual display of the required values to determine the first and second criteria for comparing manual movements and movements performed by the robot.

The graphs obtained by conducting experimental studies of the deviations of the measured points of the trajectory $l_i(x_i, y_i, z_i)$ from their projections $l_i'(x_i, y_i, z_i)$ to the midline are given in Fig. 3. Figure 3(a) shows the deviations from the trajectories during the manual movements of the surgeon and Fig. 3(b) shows those of the robot. The graphs clearly show that the deviations from the midline of the surgeon significantly exceed the deviations of the robot.



(a) Trajectory performed by a surgeon



(b) Trajectory performed by a robot

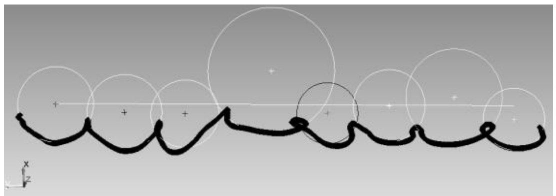
Figure 3. Graphs of the magnitude of projections l_{pi} on a linear path.

After the measurements in accordance with the first criterion, standard deviations from the linear σ_l, semilunar σ_c, and scalloped σ_f trajectories were determined. The value of standard deviations is calculated in accordance with the following expression:

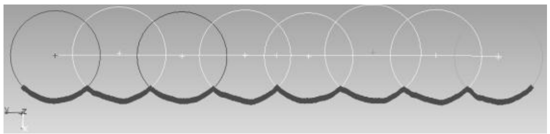
$$\sigma = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(b_i - b_{mean}\right)^2}, \tag{1}$$

where b_{mean} is the mean value of the measured quantity, b_i is the measured value at each point i, and n is the number of points.

Visually, a significant deviation of the surgeon's points relative to the robot can be shown by the example of the scalloped trajectory depicted in Fig. 4.



(a) Trajectory performed by a surgeon



(b) Trajectory performed by a robot

Figure 4. A set of scanned points of the medical instrument trajectory along a scalloped trajectory.

It is evident that the trajectory of the surgeon is less accurate in relation to the trajectory of the robot and, moreover, the surgeon also cannot exactly repeat it.

IV. Criterion II: Air Gap Accuracy

In order to cut at the required depth and width, it is necessary to maintain a predetermined amount of air d_n between the laser tip and the treated biological tissue. The second criterion is the air gap accuracy. The difference between the average value of the air gap d_m and the predetermined value d_n is the accuracy of the air gap size.

$$\delta = d_n - d_m . \tag{2}$$

The average air gap d_m on the trajectory is defined as the arithmetic mean d_i on each individual trajectory. Fig. 2 shows the air gap d_i from each point of the linear trajectory $l_i(x_i, y_i, z_i)$ of the medical instrument to its projection $L_i(x_i, y_i, z_i)$ on the plane of the table.

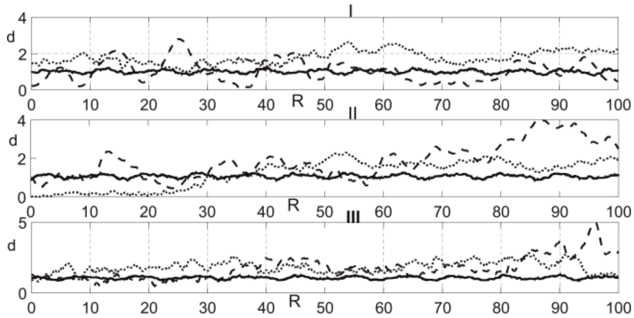


Figure 5. The graphs of the change in the air gap size d_i (mm) from the position of the medical instrument R_i (mm) for manual movements with a support point (dotted), without a touch point (dashed), and when the program moves the robot (solid) along the standard trajectories (I: linear; II: semilunar; III: scalloped).

During the experiments, both the surgeon and the robot had to hold $d_n = 1$ mm between each point of any typical trajectory and the plane of the table on which the study was conducted. Before the comparison, it was decided to divide the typical trajectories conducted by a surgeon into two categories: trajectories through which passage was carried out in the presence of a support point (i.e., the surgeon's hand touches the surface of the table during the passage) and the trajectories without touching ("in the air"). This is due to the need for the surgeon to hold the cutting tool differently during operations, depending on the openness of the operating field. The graphs of the change in the air gap size d_i (mm) from the position of the medical instrument R_i (mm) are shown in Fig. 5.

When examining the graphs, the air gap was found to be unstable under manual movements with or without a point of support compared to the robot. Therefore, together with the air gap accuracy, an additional criterion for comparing the robot's program movements and the manual movements of the surgeon was applied: the scatter value ε (mm), the difference between the maximum and the minimum air gap in each sample taken. When comparing the values of the air gap of manual movements with and without a support point, it can be concluded that the presence of a support point during the cutting process contributes only to a small decrease in the magnitude of the spread. It has also been found that, during cutting by a surgeon, the moment of contact between the tip of the work tool and the patient's biological tissue occurs periodically. In the case of using a robot, the moment of contact between the tip of the work tool and the table does not occur at all. The robot stably maintains the size of the air gap and has sufficient rigidity for a large number of diverse operations without the need for an additional support point in comparison with the surgeon.

V. Criteria for Cutting Velocities on Typical Trajectories

In order to make cuts of the required depth and width, it is also necessary to constantly maintain the given cutting velocity of the medical tool V_n at each point of the desired trajectory. If this requirement is not observed and the cutting velocity is low, the patient can receive microtraumas, burns due to excess laser radiation at the moment of cutting. At a high velocity, it is possible to undercut, so it will be necessary to make an additional pass along the same trajectory, which in case of cutting with manual movements will also cause additional injuries due to the fact that humans cannot exactly repeat the passage along the same trajectory. The third criterion is the arithmetic mean of the cutting velocity accuracy δ_{Vpr} for each pass, which allows us to estimate the cutting velocity V_j with respect to the given velocity of both the robot and the surgeon. The visual representation of this criterion is shown in Fig. 6. Its value is determined by the following formula:

$$\delta_{Vpr} = \frac{1}{Q}\sum_{j=1}^{Q}\left(\frac{\left|V_j - V_n\right|}{V_n}\cdot 100\%\right), \qquad (3)$$

where V_n is the predetermined cutting velocity and V_j is the cutting velocity of each pass along the trajectory ($j = 1...Q$, where Q is the number of passes). In turn, the cutting velocity of one pass V_j is defined as the arithmetic mean of the values of the current cutting velocity V_{tk} on the trajectory. The current cutting velocity V_{tk} is defined as the ratio of the coordinate difference of two nearby points on the path to the sampling period during scanning.

In addition, during cutting, the surgeon, in view of the incompleteness of his natural systems, can perform uncontrolled velocity fluctuations relative to the cutting velocity of one passage V_j with different amplitudes. An amplitude with significant value also can cause the patient additional microtraumas, undercuts or burns due to an excess or deficiency of laser radiation at the time of cutting at different velocities. The fourth criterion, the standard deviation of the cutting velocity σ_{Vr} (mm/s), makes it possible to evaluate the dispersion of the velocity of each cutting pass V_j (mm/s) relative to the value of the mean cutting velocity V_m (mm/s). It is determined using the following formula:

$$\sigma_{Vr} = \sqrt{\frac{1}{Q-1}\cdot\sum_{j=1}^{Q}\left(V_j - V_m\right)^2}, \qquad (4)$$

where V_m is the average cutting velocity, which is defined as the arithmetic mean of the cutting velocities from each trajectory pass V_j.

The cutting velocity accuracy δ_V, standard deviation of cutting velocity σ_{Vr}, nominal cutting velocity V_n, average cutting velocity V_m, and cutting velocity at one pass along the trajectory V_j are visually displayed in Fig. 6.

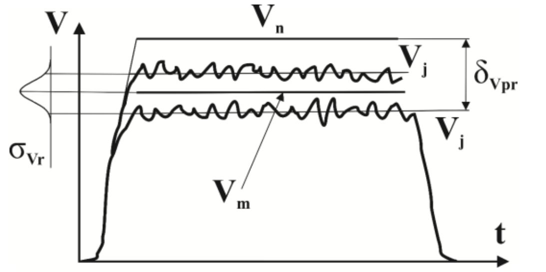


Figure 6. A visual representation of the required values for determining the third and fourth criteria for comparing manual movements and movements performed by a robot, δ_V and σ_{Vr}.

In order to determine the values of Criteria III and IV, experimental data on the cutting velocity on typical trajectories were obtained. As for the second criterion, the experimental data of typical trajectories, conducted by a surgeon, are divided into two categories: with a support point and without one ("in the air"). From the point of view of determining the cutting velocity V_j for each pass, the difference in manual movements with and without a support point is practically absent. In addition, after carrying out experimental studies, it is advisable to draw a conclusion about the identity of each trajectory in terms of the nature of the velocity of both the robot and the surgeon (i.e., regardless of the choice of the type of trajectory, the nature of the dependencies shown in Fig. 6 does not change). Therefore, all trajectories for velocity criteria are not subdivided into types, since there is no correlation between the standard velocity trajectories.

VI. Comparison of Results

The result of the comparison in accordance with the first criterion is the estimate, which is the ratio of standard deviations σ_H / σ_R on any typical trajectory (H, surgeon; R, robot). When compared on a linear trajectory, it turned out that the robot is 11 times more accurate than the surgeon; on the semilunar trajectory, five times; and on the festooned trajectory, three times. It is necessary to note that the accuracy of manual movements on each typical trajectory significantly depends on the complexity of the trajectory. Regardless of the complexity of the trajectory, the robot exercises it equally. Nevertheless, even on a complex trajectory, the robot surpasses the surgeon three times by the first criterion.

The result of the comparison in accordance with the second criterion is the estimate, which is the ratio of the air gap accuracy values δ_H / δ_R on any typical trajectory. For a surgeon who performs manual movements with a support point on a linear trajectory, it turned out that the robot is seven times more accurate; on a semilunar trajectory, three times; and on a scalloped trajectory, 12 times. For a surgeon who performs manual movements without a support point on a linear trajectory, it turned out that the robot's accuracy is equal to that of the surgeon, but on the semilunar and scalloped trajectories, the robot was 11 times more accurate.

By the third criterion, the arithmetic mean of the cutting velocity accuracy at each pass, the robot is on average two times more accurate than the surgeon conducting manual movements with a support point and is more accurate with respect to the surgeon who conducts manual movements without support points.

According to the fourth criterion, the standard deviation of the cutting velocity σ_{Vr}, it turned out that the robot is 69 times more accurate in cutting velocity than the surgeon who conducts manual movements with a support point and 26 times more accurate in velocity in relation to the surgeon who conducts manual movements without a support point.

It should be noted that the accuracy of manual movements on each trajectory depends significantly on the complexity of the trajectory, the actions of the surgeon, and the specificity of the criteria. Therefore, it is extremely rare for a surgeon to perform a more precise cut for any one criterion than a robot. In this regard, the use of the four main presented criteria should go along with additional ones, which will be outlined in subsequent works.

VII. Conclusion

The developed criteria quantify the possibility of using a robot to conduct medical operations with a diode laser in maxillofacial surgery. In addition, it turned out that, according to all the criteria, the robot exceeds the natural human systems, which allows improving the quality of operations performed due to more accurate movements. The choice of such criteria is not accidental, because these criteria are adapted to further analysis of the extended parameters of the cutting modes, where the possibilities will be added to quantitatively change the cutting velocity and the air gap size. According to the obtained experimental data and estimates, it can be seen from the comparison that the natural systems of the surgeon do not allow selecting the necessary cutting velocity and air gap between the tip of the medical instrument and the biological tissue for cutting at the required depth and width. Additionally, this is not possible because of the low accuracy of the natural systems of a surgeon. It is possible to reliably comply with the cutting modes only with the help of partial robotization of the movements of the surgeon, by programmatically controlling the width and depth of the cut. In case of partial robotization of operations with a laser medical instrument, it is possible to provide the surgeon with the necessary tools such as a robot and a "surgeon–robot" software interface that will allow performing operations of higher quality in terms of cutting modes. In this paper, there are four criteria for comparing a surgeon to a robot. In fact, there are more criteria for evaluating the joint work of a surgeon and a robot. Their extensions and branches will be presented in further works. In addition, further research is aimed at identifying reliable extended cutting modes and developing mechanisms for the cooperation between a surgeon and a robotic assistant, in other words, the development of a "surgeon–robot" interface. The developed criteria are focused on laser cutting modes; therefore, for other types of medical operations, the criteria can be radically different.

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References

[1] L. F. Zhao, A. Joubair, P. Bigras, I. A. Bonev. "Metrological evaluation of a novel medical robot and its kinematic calibration", *International Journal of Advanced Robotic Systems*, 2015, 12, p. 126.

[2] R. C. O. Locke and R. V. Patel. "Optimal remote center-of-motion location for robotics-assisted minimally-invasive surgery," *IEEE International Conference on Robotics and Automation*, 2007, Roma, Italy, pp. 1900-1905.

[3] H. Y. Jin, P. Zhang, Y. Hu, J. W. Zhang, Z. Z. Zheng, "Design and kinematic analysis of a pedicle screws surgical robot," in *Proc. the 2010 IEEE International Conference on Robotics and Biomimetics*, 2010, Tianjin, China, 1364-1369.

[4] E. A. Bazikyan and A. A. Chunikhin, "Prospects of improvement of minimally invasive laser technologies in photodynamic therapy dental pathologies," *Russian Journal of Dentistry*, vol. 20, no. 5, pp. 228-231, 2016.

[5] V. G. Suter, H. J. Altermatt, P. Sendi, G. Mettraux, M. M. Bornstein, "CO_2 and diode laser for excisional biopsies of oral mucosal lesions. A pilot study evaluating clinical and histopathological parameters," *Schweiz Monatsschr Zahnmed*, vol. 120, no. 8, pp. 664-671, 2010.

[6] G. Kronreif. W. Ptacek, M. Kornfeld, and M. Furst. “Evaluation of robotic assistance in neurosurgical applications,” *Journal of Robotic Surgery*, 2012, vol. 6, pp. 33–39.
[7] L. Balasubramani, D. A. Milliken, J. H. Shepherd, T. E. J. Ind, “Differences in hand movements and task completion times between laparoscopic, robotically assisted, and open surgery: an in vitro study,” *Journal of Robotic Surgery*, 2011, vol. 5, pp. 137–140.
[8] A. A. Chunikhin, M. Y. Sahakyan, S. I. Gazhva, E. A. Bazikyan, “Development of nanosecond laser module built in the robotic multifunctional surgical complex for minimally invasive therapy of maxillofacial area pathology and estimation of its effects on blood plasma,” *Sovremennye Tehnologii v Medicine,* 2016, vol. 8, no. 4, pp. 30–35.
[9] H. Jelínková, “Lasers for medical applications: diagnostics, therapy and surgery,” *New Delhi, Woodhead Publishing Limited*, 2013, ch. 1, pp. 87-89.
[10] F. W. Neukam, F. Stelzle, “Laser tumor treatment in oral and maxillofacial surgery,” *Physics Procedia*, 2010, vol. 5, pp. 91-100.
[11] Manipulating Industrial robots – performance criteria and related test methods, ISO 9283:1998.

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