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RobIn Heart 0, 1, and 3 – mechanical construction development

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Abstract. The project called "Polish Cardiosurgical Robot" has been developed by Foundation for Cardiac Surgery Development since year 2000. Within the project the telemanipulator to perform the endoscopic cardiosurgical operations has been designed, manufactured and examined. In the following paper the development of construction of arms for RobIn Heart 0, RobIn Heart 1, RobIn Heart 3 versions of the robot as well as the fixing system has been presented. In the preliminary phase of the project the requirements for mechanical construction were analyzed. Additional requirements enhancing functionality of the construction were also defined. Analyses of the planned development of the construction and ways of its possible applications were performed.

Key words: medical robots, examination of robots, construction of robots.

1. Introduction

Nowadays, cardiosurgical telemanipulators, frequently called robots by surgeons – that is why these terms will be used interchangeably, are the most demanding applications of robots. The construction of this type of robots comprises several aspects e.g.

- high accuracy requirements of positioning – less than 0.1 mm,
- specific kinematics enabling tool insertion into a patient's body through the port,
- miniature tools as well as the last DOFs of a robot,
- necessity of sterilization.

Currently there exist two constructions of cardiosurgical robots used in practice, i.e.: Zeus produced by "Computer Motion" [1] and "DaVinci" by "Intuitive Surgical" [2–4]. Their large cost, which is about 1.ooo.ooo$ makes them unavailable to Polish hospitals for financial reasons. This was why the attempts to prepare similar constructions were undertaken in Poland. However, it was decided not only to copy but also to undertake the challenge of constructing an improved version of the robots mentioned above, at least in some aspects.

Polish manipulator was named RobIn Heart. Since 2000 it has been realized within the research programme of The Foundation for Cardiac Surgery Development [5]. The mechanical constructions have been developed in two centers: in the Institute of Machine Tools and Production Engineering at Technical University of Łódź and at the Warsaw Polytechnic.

The mechanical part of the robot consists of several subassemblies: the fixing system with passive DOFs, the arm, the tool and the drive system of the tool. The functional quality highly depends on the quality of these subassemblies. In the following paper selected assumptions of the arm construction have been presented. Furthermore, the constructions designed and manufactured at University of Łódź for RobIn Heart 0, RobIn Heart 1 i RobIn Heart 3 as well as the fixing system have been described.

During the construction process of the robot many more problems were tackled and solved, which was described in detail in other publications. Two versions of control systems prepared in The Foundation for Cardiac Surgery Development, were presented in e.g [6]. The description of forward and reverse kinematics was presented in [7], Polish constructions are compared to Zeus and Da Vinci in [8].

2. The influence of a task on the construction features

2.1. Stability of the port location and kinematics of the robot. The construction of the robot is highly influenced by the fact that cardiosurgical operation is performed as a laparoscopic one. Due to that, the tool has to be inserted into patient's body through the relatively small hole (1 cm) called the port, and the working space is situated under the skin layers. It results in the specific kinematics of the manipulator enabling the tool inserting through the fixed port, and additionally enabling the port position setting according to the operation requirements and anatomy of the patient operated on.

The most natural for this purpose is the spherical kinematics of the manipulator, the center of which is placed in the port. There are several ways of spherical robot construction for the assumption mentioned above.

Principally, there are three methods of obtaining stability of the port: kinematic, passive and active.

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Passive stability of the port location is the solution similar to the classic laparoscopy. The point of the tool insertion into the body is treated as a joint of 4^{th} class taking away 2 DOFs. In other words it is the point of the tool support. In order to take away all 6 DOFs the arm of the robot must take away 4 DOFs: 3 of them are defined by fixing the external ending of the tool. In Zeus robot it is performed by SCARA type of manipulator. In order not to get over-rigid manipulator, two joints between the arm and the tool have to be not driven (the Cardan joint). The following DOF – rotation of the tool around its axis – is usually driven by electric motor. The disadvantage of that solution is loading the port with forces coming from the tool, as well as the dependence of the tool location on the port movements. The flexibility of the tool grows considerably.

Active stability of the port location uses the redundancy of the kinematic system. The robot has got two DOFs more than necessary for the tool moving. Stabilization of the port location is performed on the level of control. The port (to be more precise – the body just around the port) is treated as an obstacle. The robot is to reach its working points avoiding these obstacles. The kinematics of such a robot can be very different: from open systems to closed ones.

Kinematic stability of the port location involves designing the robot of spherical kinematics with the centre of that sphere in the point of the tool insertion into the patient's body. It requires comparatively complicated mechanical systems based on parallel mechanisms. Thanks to them, it is possible to construct the kinematic structure, in which one of the elements can rotate around the axis being comp1letely beyond the mechanism (Fig. 1). It should be mentioned that in this construction, in spite of remotely controlled DOFs, there must be present some additional joints to set up the point, around which the tool rotates coincidently with the hole in the human body. It must be performed every time before an operation.

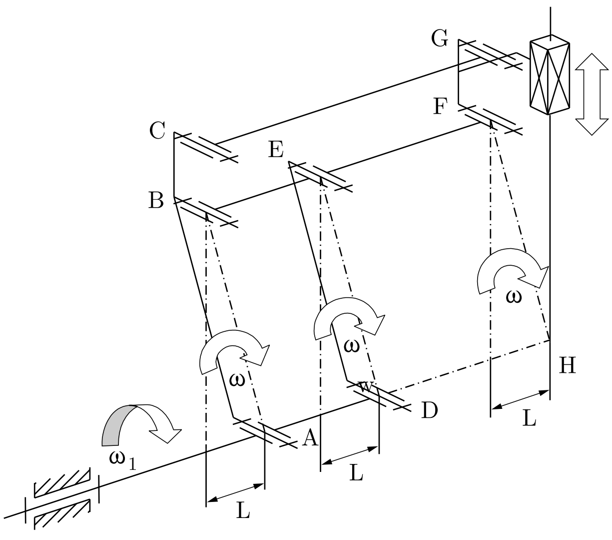

Fig. 1. Kinematic scheme of constant point mechanism

2.2. Precision of the manipulator. Another feature of the manipulator performing surgical operations, except for the stability of the port location, is its accuracy, repeatability and resolution. When defining these assumptions, the most precision demanding part of the operation was taken into account: joining the coronary artery bypass with the coronary artery. The task of a surgeon is to join two vessels the diameter of which is 3 mm. The joining is performed by means of the needle of 0.2 mm in diameter by placing sutures every 1 mm. Based on these assumptions, the conclusions were derived that the precision of the manipulator movements should not be worse than 0.1 mm. That precision can be evaluated by multidirectional repeatability and resolution of a robot. It is also influenced by many different conditions. One of them is certainly clearance in the drive system. It is easy to notice that clearances in drive systems affect the accuracy of the whole mechanism in various ways. The clearances in the first three DOFs exert the strongest influence on the repeatability of the whole mechanism. The most important mechanical factor is flexibility of a robot and the rate of friction forces both of which highly influence the multidirectional repeatability. Friction forces cause variations of the torque affecting the drive system when positioning in the same point from different directions. Subsequently, flexibility of the drive system causes its displacement under the influence of the torque applied. Superposition of these factors results in hysteresis in the drive system. The next factor affecting the precision is resolution of the position measuring systems and static error in the displacement feedback loop.

2.3. The size of the workspace and the range of joints movements. Except for accuracy and kinematics of a manipulator it is the size of a workspace which has to be taken into consideration during the constructing process. The highest range of displacement during operation takes place when inserting the coronary artery bypass from the chest artery especially when performing concurrently two coronary artery bypasses from both chest arteries. The first stage of such an operation is the chest arteries preparation up to clavicle. Then, they are turned back and inserted into heart. That is why the range of displacements is about 40 cm. Because of the asymmetrical position of the ports in relation to that space, it should be accepted that the range of the linear movement is about 30 cm. The range of the angular displacements should be about 150° around the axis perpendicular to the sternum and about 80° around the axis parallel to the sternum. It should be also mentioned that the whole arm is additionally linearly and angularly moved in relation to the patient by means of the passive DOFs. The ranges of the movements can be thus displaced. The additional problem is a proper selection of the wrist joints movements range. Due to assumed high maneuverability of the robot the decision has been made that the rotations of the wrist joints should allow any orientation of the tool in the workspace.

2.4. The collision space. One of the important inconvenience of the actual construction of DaVinci and Zeus robots is large space occupied by their arms during an operation. It results in frequent collisions of the arms of the robot with themselves as well as with the body of the patient. In Da Vinci robot one of the arms can collide with the clavicle making impossible to access some parts of the workspace. Therefore it has been assumed that the dimensions of the arms should be as small as possible, and the fixing system should prevent their collision during an operation. Additionally, the linear drive should be designed as the telescopic one – after inserting inside a patient's body, the length of it should be smaller.

2.5. Dynamics of the manipulator. When constructing any robot the main feature of it is its dynamics. Nevertheless, a telemanipulator is a specific kind of robot. It is controlled by a man and it copies human movements. That is why its accelerations and velocities do not have to be better than these of a man. They can be even much worse, because the precision movements are usually performed much slower. In a telemanipulator, the movements are scaled in order to enhance the precision. In other words, it can be assumed that the necessary level of velocity is a few cm/s, and the torques are close to the static ones. However, these assumptions have been modified after taking into consideration the possible directions of the robot's development as well as modification of the strategies of operation of the beating heart. At present the operations are performed holding down the heart muscle with the special stabilizer preventing the heart muscle from the movement. This results in a loss of the heart efficiency. In many comments, the cardisurgeons showed their expectations as to the construction the robot which would be able to follow up the beating heart muscle movement. After heart movements analysis, it was determined that the necessary velocities should not be greater than a few cm/s, and the accelerations about 1m/s^2. Adding some margin, it has been assumed that the robot should allow accelerations of $2\ \text{m/s}^2$. However, that assumption was made only for RobIn Heart 1 and RobIn Heart 3.

3. RobIn Heart 0 – construction and properties

Several constructions of the RobIn Heart arm have been analyzed. Three of these constructions were manufactured as prototypes and examined, namely RobIn Heart 0, RobIn Heart 1, RobIn Heart 2. Robots RobIn Heart 0 and RobIn Heart 1 were designed by the team of engineers of the Institute of Machine Tools and Production Engineering at Technical University of Łódź and manufactured in the workshop of the Institute. Robot RobIn Heart 2 was simultaneously developed under the supervision of Krzysztof Mianowski PhD, MEng. at Technical University of Warsaw [9]. Currently, RobIn Heart 3 is being developed by the Institute of Machine Tools and Production Engineering as a modification of RobIn Heart 1 version.

3.1. The construction of the RobIn Heart 0. RobIn Heart 0 was built in 2002 (Fig. 2). Its spherical structure consists of the parallel mechanisms displacing the axis of the second DOF into position outside the whole mechanism (Fig. 3). The first DOF – the rotational joint – is driven by means of the AC motor integrated with Harmonic Drive gearbox and with cross bearing. From the theoretical point of view, the range of movement of that DOF is limited only by the wiring system flexibility. However, the range of movement has been limited to 180o, because greater range could result in possible collisions of the robot with the patient's body. The second DOF is the rotational joint the axis which is displaced outside the mechanism. It comprises the parallel mechanism system. The range of rotation angle is 150°. In order to avoid disadvantageous phenomena in parallel mechanisms acting near the singularities, the system of doubled parallel mechanisms has been applied. The drive of the first unit of these parallel mechanisms – the vertical beam – is performed by means of the doubled crank system with the Maxon brushless motor and rolling screw.

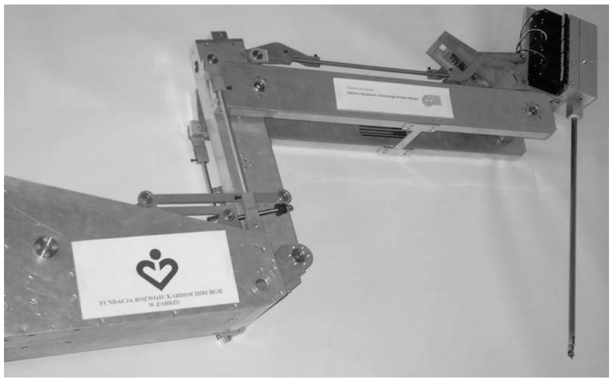

Fig. 2. The arm of the RobIn Heart 0 robot

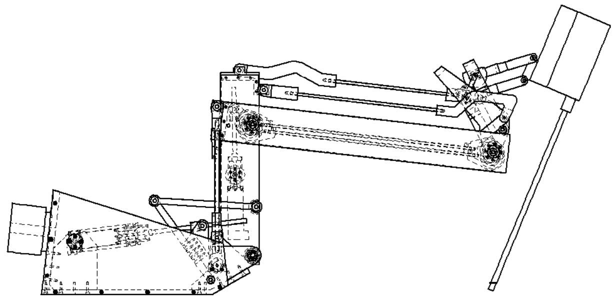

Fig. 3. The drive systems of 2nd and 3rd DOF of RH0 robot

The mechanism of the tool line feed – the third DOF – also contains the parallel mechanisms. The brushless motor with the planetary gear has been placed in the vertical arm in order to transfer the loads as close to the base as possible. Therefore, the drive system is mounted inside the horizontal beams and is performed by means of the string system with eccentric cams. The rotational movement is further transferred onto the system of two parallel mechanisms connected with joints and two fragments

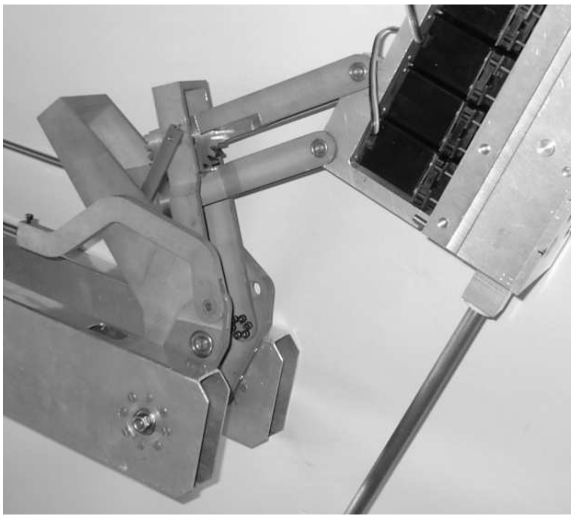

Fig. 4. The tool line feed mechanism in RobIn Heart 0

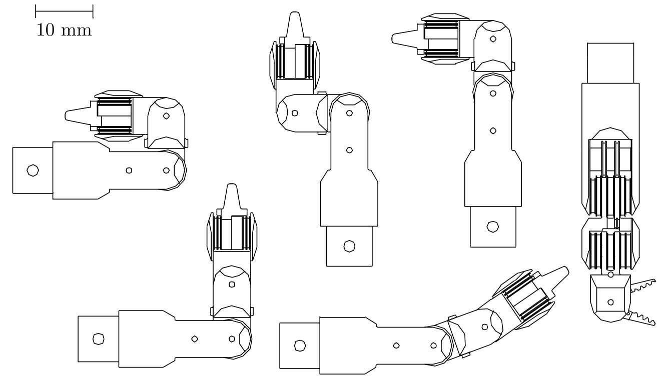

Fig. 6. Manipulate abilities of the wrist

of the gears (Fig. 4). Superposition of two movements of these parallel mechanisms results finally in linear motion. That solution eliminates the necessity of applying the long (ca. 0.5 m) and linear guide that collides during operation.

The further DOFs of RobIn Heart 0 were used in the wrist drive system. The tool applied in RobIn Heart 0 is presented in Fig. 5 The working part of the wrist consists of quick connector 1, tube 2, in which the strings driving the tool 3 are placed, two rotational units 4 and 5, a pair of tools (pincers) 6.

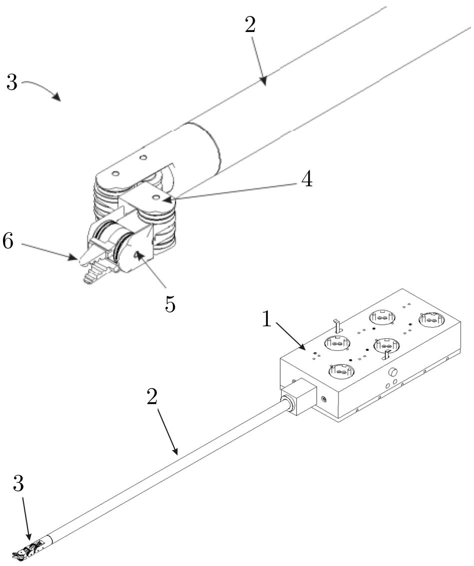

Fig. 5. The tool of RobIn Heart 0

At the end of the arm the plate containing six servomotors is mounted. The separator is fixed to the plate dividing the necessarily sterilized part from the non-sterilized part. The wrist units and the tool are driven by means of motors attached to the arm of the robot. The drive is transferred through disks in the separator onto the driving beams in the quick connector, and further by means of the strings to the wrist units. The strings move in the closed loop rewinding through appropriate beams. The tightening system of the strings comprises additional disks attached eccentrically and enabling manual control of tightening the strings. Placing two rotational units 4 and 5 in the tool results in redundancy of the kinematic system of the robot as well as in enhancing maneuverability of the wrist (Fig. 6) allowing to reach any orientation including "backward" work.

3.2. Properties of the RobIn Heart 0. RobIn Heart 0 has been thoroughly technically examined. During the examining it was found that its construction is far less rigid than it was expected after numerical calculations. The differences come from the fact that the numerical calculations did not take into account flexibility of the bearings and flexibility of interference of joints in places of bearings and beams mounting. The additional source of flexibility is an openwork construction of the linear drive and open frame of the first unit – the nacelle. High flexibility of the whole arm of RobIn Heart 0 along with big mass of the wrist drive (2 kg) caused very low values of eigenfrequencies of the arm (ca. 5 Hz). The additional disadvantage of the analyzed construction turned out to be the application of long strings in the drive system of the wrist. It resulted in loss of rigidity and eventually high hysteresis of the drive system. RobIn Heart 0 acting was also consulted with surgeons. They pointed to high functionality of the wrist construction, especially the possibility of the "backward" acting. However, as far as the arm construction is concerned, the ranges of movements of RobIn Heart 0 are much exceeding the necessary movements to perform the cardiosurgical operations. In the second DOF it would be quite sufficient to have the angular range of 80°(instead of 150°applied in RobIn Heart 0), and the range of movement of the linear unit could be limited to 0.3 m (instead of 0.4 m).

4. RobIn Heart 1 – construction and properties

4.1. The construction of the RobIn Heart 1. Based on the analysis of RobIn Heart 0, the second version of the tool arm of the robot called RobIn Heart 1 has been constructed (Fig. 7). The changes in construction had three aims: decreasing mass of the wrist drive system, increasing rigidity of the arm and drive systems, decreasing overall dimensions, especially the transverse size.

Fig. 7. RobIn Heart 1

The increase in the arm rigidity was obtained by means of applying closed profiles of all elements of the arms and applying bigger and more rigid bearings with appropriate preload. The operating properties of the wrist were enhanced by modifications of its drive system. Owing to the limitation of movement range of the second DOF to 120°, the structure of the parallel mechanisms was simplified, which resulted in high compactness of the construction (Fig. 8).

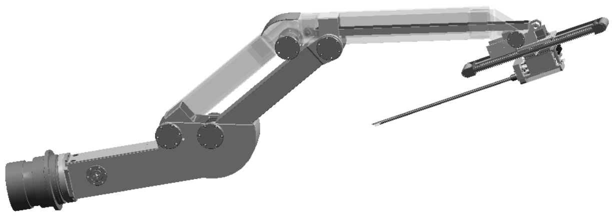

Fig. 8. RobIn Heart 1 – the arm construction

The linear drive of the tool insertion into the patient's body is the third DOF. In RobIn Heart 1 the original construction has been applied and is patented [10]. The telescopic linear drive consists of the frame, the bar and the output element i.e. the base of the tool drive system. Both ends of the bar are equipped with the rollers and bearings the axes which are perpendicular to the movement direction. The bar is driven by means of the Maxon EC22 motor, gear pair in series and the roller screw. The drive of the output element is realized by means of two fragments of a belt, one end of which is fixed to the frame, the second one – to the output element. The belt rewinds the rollers mounted in bearings in the bar. The advantage of that drive system is the small dimension of the space occupied by the working mechanism, the length of which is equal to the length of the bar. It is approximately twice as little as the range of the mechanism movement (400 mm). Except for the application, advantages the whole construction is compact and esthetic. The width of the arm varies from 70mm at the base to 50mm at the linear drive fixing. It is of a great importance especially in case of three arms working together one next to another. The drives of every DOF are hidden inside the construction elements, and the screens protect all the elements which are inside. It enhances safety of the operator. The electrical wiring has been situated inside the beams in order to protect them mechanically and electromagnetically. Decreasing mass of the wrist drive has been obtained by replacing modeller servomechanisms by much smaller brushless motors the diameter of which is 6mm integrated with planetary gears. Due to these changes, the wrist drive block along with the drive system situated in the top part of the tool covers the space of $46 \times 48 \times 90$ mm. Mass of these elements is ca. 0.4 kg, which is five times smaller than in RobIn Heart 0. Kinematics of the wrist is similar to RobIn Heart 0, but the dimension was reduced from 10 mm to 8 mm (Fig. 9).

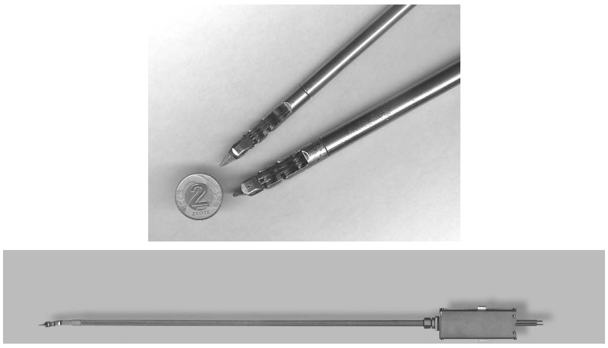

Fig. 9. The tool of RobIn Heart 0 (diameter 10 mm) and RobIn Heart 1 (8 mm)

During the current works three tools were built, i.e. forceps, scissors, scalpel, each of the tools consists of identical driving elements and links with the exception of the last two ones finished with end-effectors. This unification of the construction is a significant technological improvement.

4.2. Properties of the RobIn Heart 1. Having constructed RobIn Heart 1 the examination of it was performed. One of the measured parameters was rigidity of the arm. According to the intentions it turned out that obtained rigidity was 28600 N/mm (4850 N/mm for RobIn Heart 0). The other analyzed parameters were resolution and repeatability of the robot. The parameters were measured by means of three contactless inductive sensors of displacement placed in three mutually perpendicular directions.

The measurements were performed in the position corresponding to the central configuration of the DOFs, in the close neighbourhood to the point of the gravitational

forces balance. The robot was standing freely and was not loaded with forces from the tool and port interaction. The point of measurement was situated on the tool in the position allowing to avoid influence the flexibility of the tool on the results of measurement.
The resolution measurement was performed by oscillatory movement of the arm in one DOF with increasing amplitude. It was observed that the minimal displacements were from 0.008 to 0.013 mm depending on the analyzed axis. They corresponded to the movement of motor measured as 4 to 6 impulses of the encoder.
The repeatability measurement was performed for several different directions of positioning in the measure position, the positioning was repeated 30 times and the obtained position was measured. In all measurements the repeatability varied not more than from ±0.01 mm to ±0.02 mm.

5. RobIn Heart 3 – construction

Along with very good results of rigidity and accuracy of the robot, some disadvantages were also detected. One of them is electromagnetic interference caused by Harmonic Drive motor of the first DOF. It is the AC motor equipped with the inverter. The second disadvantage was high level of noise of the gear in the linear drive system. Another one was a highly complicated and prone to breakdown drive of the wrist. These disadvantages were gradually eliminated during the construction of the following version of the arm: RobIn Heart 3 (Fig. 10).

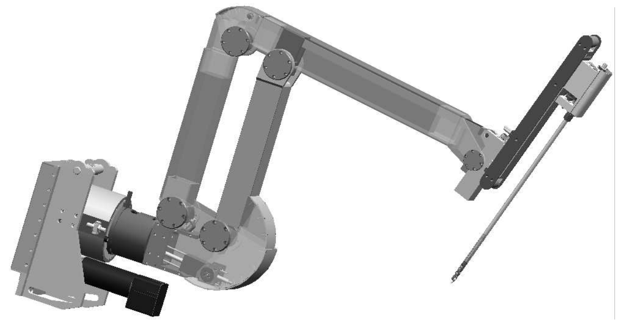

Fig. 10. RobIn Heart 3

In the robot the Maxon EC45 motor was applied for the first DOF along with the planetary gear (10:1 ratio) of the reduced clearance (3') and the cylindrical gear with clearance elimination system. In the linear drive (3^{rd} DOF) the gear was replaced by the toothed belt transmission. The RobIn Heart 3 arm is assembled. The modified construction of the wrist drive is currently constructed. Another important improvement of RobIn Heart 3 is the control system modification. In RobIn Heart 0 and RobIn Heart 1 the control system based on industrial computer PEP was applied. In RobIn Heart 3 the PC computer with Widows system and servomotor control card Galil GMC 1842 has been applied. That solution highly simplifies the construction and reduces costs of the control system. The disadvantage of unreliability of the Windows system can be eliminated by inserting the program into the memory of the Galil card.

6. The arm fixing system

The arm of RobIn Heart is of the spherical structure. Therefore it has to be fixed into the structure of three DOFs enabling the intersection point of the DOFs axes to be aimed at the port in the patient's body. That aiming is performed at the beginning of an operation, and then the DOFs of the fixing system are blocked. They stay still during the whole operation. The structure suggested and performed during the project fixes the arm to the base standing on the floor (Fig. 11). The base contains the horizontal linear guide. The beam moving along that guide is the first unit of the fixing system. The second unit is mounted rotationally in relation to the beam, the axis of the rotation angle versus horizontal level is ca. 45°. The third unit is assembled to the second one by the rotational joint of the axis which is perpendicular to the axis of the second unit. Displacement of the first DOF enables to set the arm perpendicularly to the operation table, displace the second DOF – parallel to the table, and displace the third DOF – vertically. The position of the second and third joint axes should be selected in the way allowing the axes intersection to be situated as close to the centre of gravity as possible. Should that condition be met, the system will be statically balanced and the surgeon will be able to set the robot comfortably without great effort.

Fig. 11. The fixing system of the single arm

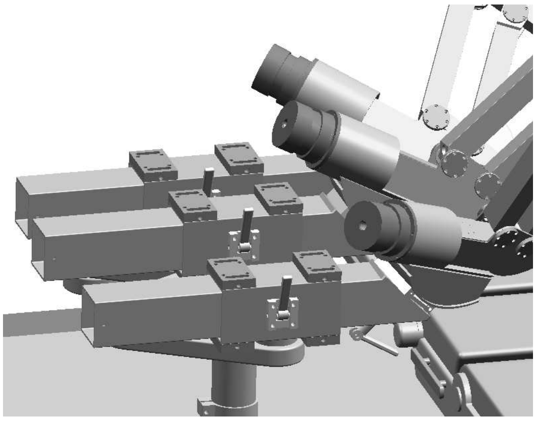

Fig. 12. Fixing system of three arms

It should be mentioned that three arms of the robot have to operate simultaneously during the operation. The fixing system proposed is very advantageous, because it is highly compact and it does not occupy much space, especially close to the parallel axes of the linear guides (Fig. 12). At some positions of the elements, there is no possibility of collision of the arms.

Currently the other systems of fixing are being constructed in the Institute of Machine Tools and Production Engineering at Technical University of Łódź. The fixing system of the robot to the surgical table and to the ceiling above the table are being designed. These constructions seem to be of a great importance because of little space they occupy in the neighbourhood of the operation table. Fixing to the ceiling additionally provides the possibility of easy movement of the arms out from the operating space at the moment of necessary operation break. However it should be mentioned that the system requires high rigidity of the mechanism which is not easy to obtain.

7. Conclusions

In the paper the way of development of manipulating part of the RobIn Heart robot has been presented. It is easy to notice that except for the similar assumptions for all constructions, there are many significant differences in details of construction especially between RobIn Heart 0 and RobIn Heart 1, which was caused by the fact that at the beginning of the project the assumptions were known only theoretically. Experimental tests of the real arm showed the importance of different assumptions, particularly the rigidity of the manipulator. The possibility of the robot evaluation by the surgeons turned out to be of great importance. Their earlier opinions were not specific enough. Therefore, it was hard to apply all their suggestions when defining the assumptions of the construction. Only the experimental evaluation of RobIn Heart 0 allowed to gain information for further construction.

Experience from the first prototype has been fully utilized. As it was showed in section 4.2 the second prototype of RobIn Heart 1 turned out to be a highly successful construction redundantly meeting the requirements of the project assumptions. This redundancy was not high enough to expect the reproach of overdimensioning the construction. As the pioneering enterprise, this is not the ultimate version of construction. The apparent disadvantages have been avoided in the following version. Summarizing, it can be stated that the way of constructing the consecutive versions of RobIn Heart robot prototype resulted in achieving the arm construction which successfully meets functional properties required.

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