

# An Advanced Robot -Robin Heart (A Surgeon without Hand Tremor)

Aruna.D.Mane, Sirkazi Mohd Arif, Waleed Abdu Rahiman

**Abstract-** The paper presents the current state of works conducted by the Zabrze team under the Robin Heart surgical robot and the Robin Heart Uni System mechatronic surgical tools project as a example of introducing technology and materials advances for progress in surgical robots. 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 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. A system to verify the forward kinematic and the trajectories for the Robin Heart master device was implemented. The system consists of hardware based on incremental encoders connected to a data acquisition card and software programmed in Matlab and LabView to create an interface between the system and the user. The system verifies the position of the tool tip when different values for the joints are configured. The visualization of trajectories is also possible after saving a routine of movements made by the user. Analyses of the planned development of the construction and ways of its possible applications were performed. The special intention is to show the review of the current and futuristic medical robots needs in the area of material science.

**Keywords:** Medical robots, Examination of robots, Construction of robots.

## I. INTRODUCTION

The idea of Robot is not new. For hundreds of years man has been imagining intelligent mechanized devices that performs human like tasks. He has built many types of Robot. The market for medical tele-manipulators used in surgery is expanding very dynamically. The development of medical robotics results in the construction of tools of direct via technology tele-medical contact with patients and medical personnel. The robotic systems are information systems and as such they have the ability to interface and integrate many of technologies being developed for and currently used in the operating room. Robot invented for less, minimally invasive cardiac surgery is a computer-controlled device, located between surgeon's hands and the tip of a surgical instrument. Basic requirements for this device are first of all high reliability, stable operative field of view, direct surgeon control and high level of precision.

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The Robin Heart is a Europe's first heart surgery robot system with whole, original Polish design. Precise and optimally adapted to the surgeon's manual dexterity, it also helps him make the right decisions. Around 4 million minimally-invasive surgeries are performed in the world every year. The procedures are performed by means of special instruments inserted through small incisions in the patient's body. The aim is to limit the operative field and protect surrounding tissue, which could be damaged if a traditional surgical technique was used. The number of endoscopic procedures, less invasive than traditional surgery, performed through natural orifices in the patient's body, or through special openings called ports, is on the rise. The success of the procedures largely depends on the instruments used. Unfortunately, typical endoscopic (laparoscopic) instruments reduce precision and make the surgery more difficult because they add to hand tremor and almost completely eliminate the natural sense of touch. Additionally, the surgeon does not have a direct view of the operative field—a camera inserted into the body through a third opening transmits the image to a display. So the surgeon's task is not easy. An ideal non-invasive surgery can be compared to the house renovation through a keyhole without disturbing the household members. Across the world, physicians and engineers are working to develop increasingly effective instruments to enable surgery with the use of the latest technology. But how can one enhance instrument precision and maneuverability, which are so important in the case of surgery on the beating heart, for instance? Surgical robots provide such capabilities.

Robot is intended to keep the surgeon in the most comfortable, dexterous and ergonomic position. The basic principle of manipulator construction is that of a serial architecture of joints and links with a fixed remote centre in corporeal wall. The surgeons control via a human-machine the movements of tools. The main task of robot is reliable mapping of surgeon hand movements (setting of position/velocity/acceleration of other physical quantity) onto the movements of tool arm, through calculation of control signals for its motors. Contemporary the history of medical robotics in surgery has been created by the da Vinci (Intuitive Surgical, in Mountain View, Calif., IS) & Zeus (Computer Motion Inc. of Goleta, Calif., CM, currently merged companies), but in several laboratories and universities the next generation of surgical robots are waiting for crossing from laboratory to surgery room. The Foundation of Cardiac Surgery Development (FCSD) realizes project of polish robot useful for cardiac surgery. The multidisciplinary team prepared families of robot prototypes named Robin Heart and mechatronic tools. New, semi-automatic tools are in the process of emerging our Robin Heart Uni System.

## II. RELATED WORK

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 1.000.000\$ 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 program 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 Lodz 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 Lodz for Robin Heart versions 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].

## III. PROBLEMS REGARDING ROBOTS

The development process needs new technologies, new materials, new constructions and design. If the cost of these systems remains high and they do not reduce the cost of routine procedures, it is unlikely that there will be a robot in every operating room and thus unlikely that they will be used for routine surgeries. An average operation uses up \$1,500 in consumable tools. Da Vinci lists for \$1.3 million (The new da Vinci HD SI released in April, 2009 currently sells for \$1.75 million), and IS economist estimates that high-volume hospitals will spend another \$525,000 per year for service contracts and parts for the three units. The da Vinci’s robotic surgical instruments have a fixed usage life of 10 procedures per instrument. This disadvantage is related to material and construction used in tools. Current instruments have restricted degrees of motion; most have 4 degrees of freedom DOF (motion), whereas the human wrist and hand have 7 DOF. The very important problem is developing the driving system of the wrist and the gripper. The following systems are possible: the follower-based system and the string system. For the follower drive they are as follows: from  $\pm 200$  to  $\pm 500$  – just like in the Zeus robot.

For the string drive they usually are  $\pm 900$  – just like in DaVinci robot and the Robin Heart 1. The Robin Heart has 7 DOFs – it is redundant. In Robin Heart 3 and Uni Tools 1 the combination of follower and string system were introduced. The special relation between the elasticity and stiffness in Robin Heart Uni Tools 0 was reached using connection of stainless steel and Nitinol. Many laboratories are currently working on systems to relay touch sensation from robotic instruments back to the surgeon and on improving current methods and developing new devices for suture-less anastomoses. For laparoscopic procedures special sewing devices, ligating instruments, knot pushers, clips and clip applicators have been developed. The clamp is an essential tool during surgery where blood flow to an organ must be stopped or controlled. There is a need for secure and easy methods for suturing in laparoscopic surgery. Laparoscopic suturing can be done with a suture, using automatic sewing devices or clips. Knotting instruments require a two forceps technique, while for sewing devices one working channel is enough. The future is open for semi automatic tools for MIS. As a example, Medtronic, Inc. has introduced the world’s first minimally-invasive epicardial lead placement tool. Material inserted in blood system should not cause irreversible damages of proteins’ structure, blocking of enzymes’ activity, changes of electrolyte’s composition, damages and releasing of the blood cells’ contents, blood clotting, initiation of toxic, immunological and mutagenic reactions. On the basis of the in vitro tests of the implants made from AISI 316L steel used in bone and maxilla facial surgery it was found out that passive-carbon coating on surfaces guarantees to the implants a very good resistance to the pitting, stress, crevice corrosion and demonstrated a good biotolerance. The deposition process of the carbon coating, using rf PACVD method, was carried out at the Institute of Materials Engineering of the Technical University of Lodz (S. Mitura and P. Niedzielski). The robot Robin Heart 1, in this type these NCD have been used on element performed at the Technical University of Lodz, have been designed by Podsedkowski/Nawrat. The degrees of freedom DOF are driven by electric, brushless motor. The second and third DOFs are driven by brushless motors, roller screws and system of strings. In order to enable sterilizing of the manipulator, the construction makes possible fast and not complicated disconnection the drive part of the bunch from the manipulating part. The separable part does not contain any elements requiring lubrication. Robot consists of many small elements, given under relatively huge load (some millimeters of diameter of wheel, with half millimeters strings, shifting elements oneself in relation to itself of etc.). The experience in clinical beating heart cases has demonstrated the importance of small instrumentation to successfully complete these procedures. The working tips of microsurgery instruments must be smaller than 5 mm in order to not obscure the small endoscopic field of view and efficient maneuver in the small space within the chest. Robots can damage during operation. For example N. oliakos et al. reports a rare case of a da Vinci robotic arm failure during a laparoscopic robot-assisted radical prostatectomy.

The articulation joint of an Endowrist needle driver was broken and positioned at such an angle that made it impossible to remove through the trocar. In addition, it was later discovered that a small piece of the instrument was detached and remained inside the abdomen of the patient without even having been identified on subsequent radiological evaluation.

#### IV. HYPOTHESIS & INITIAL STEP

The Foundation of Cardiac Surgery Development (FCSD) in Zabrze began in 2000 the grant for realization of the prototype of a robot useful for cardiac surgery. The multidisciplinary team including specialist in medicine and techniques during three years prepared families of robot prototypes named Robin Heart (Fig.1).



Figure1. The Robin Heart

The goals of the project were:

- Safe, reliable and repeatable operative results with less patient pain, trauma and recovery time
- Support the technology breakthrough - significant increase of the number and type of minimally invasive procedures available to patients.
- Friendliness guarantee both for the patient and surgeon.

##### A. 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. 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 situated completely beyond the mechanism. 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 coincidentally with the hole in the human body. It must be performed every time before an operation.

##### B. 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.

##### C. 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  $150^{\circ}$  around the axis perpendicular to the sternum and about  $80^{\circ}$  around the axis parallel to the sternum.

##### D. The Collision Space

One of the important inconveniences of the actual construction of Da Vinci 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.

##### E. 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 is close to the static ones. After heart movements analysis, it was determined that the necessary velocities should not be greater than a few cm/s, and the accelerations about  $1\text{m/s}^2$ . 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.

**F. Techniques Analysis for Cardiac Surgery**

To provide all necessary functionality of modern laparoscopic devices, robot Robin Heart gives user a three degrees of freedom to orientate in space, fourth one is responsible for opening and closing jaws of the tool and the fifth one increase the manipulation skills to avoid obstacles, or like Robin Heart allows to work “backwards”. Standard laparoscopic device has got a limited mobility and do not offer very sophisticated types of movement that are provided by a robotic systems. To see the differences in a mobility between two various Robin Heart instruments, a tool workspace was calculated for a robot equipped with a standard laparoscopic device and a more advanced robotic instrument (Fig.2.). Having a workspace sphere calculated for the entire robot instruments it is very easy to verify the goal of using a suitable device for a proper surgery treatment. Combining this workspace with a geometric position surface we were able to calculate the total range of movement for both robotic instruments inside the patient body.

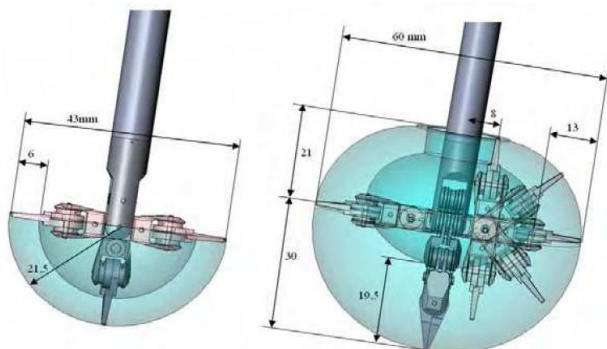


Figure2. Instrument workspace

a) Standard Laparoscopic tool, b) Robin Heart tool

**G. Virtual Reality Modeling**

The Robin Heart system research and the modeling work is using an EON Reality Virtual Reality latest technology. Because VR is a very intuitive solution this type of modeling gets much more popular nowadays helping surgeons and even patients to understand very complex procedures much more clear and efficient. Nowadays in a RH project VR technology is implemented in four different areas:

- As a training station in surgeon education process,
- As a tool used for a surgery treatment procedure planning with a step by step briefing in an advisory voice operated system with an external database,
- To verify a different construction versions in aspect of ergonomic and functionality.

FCSD has used a Virtual Reality technology to create several training station that helps user better to understand the benefits of robotic surgery and how to use a robotic

system during the surgery treatment. The total impression of immerse in a computer world was emphasized by using a special active stereoscopic projector and a shutter glasses. The total Virtual Reality scene was completed with a three separate Robin Heart robots that can be manipulated realistically with all of their functionality; endoscope camera viewport displayed in a PIP technology (picture in picture), human model with basic organs which might be exchanged to ones from a patient CT or NMR; surgery room with a surgery table, lamps and all the basic equipment. Prepared VR model and also a Robin Heart training system was created in a EON Professional, and fully supports real time rendering with advanced graphic effects, contact between the objects, friction, gravity and a mass properties. Foundation for Cardiac Surgery Development is using virtual model to verify the choice of using a specific instrument inside the surgery area by comparing the size and the shape of the different workspaces; to plan and simulate the surgery treatment with step by step instructions for a surgery room choreography optimizing the position of each robot arm for different procedures to set the correct trocar ports between the patient ribs; to educate how to use an endoscope camera during the surgery procedure.

**H. Planning of Robot Assisted Cardiac Surgery**

Pre-operation planning means several researches using computer and physical models, performed to reach optimisation surgery effect by optimisation of methodology, materials, devices and techniques of surgery. Modern medical imaging methods like computer tomography (CT), nuclear magnetic resonance (NMR) enable the surgeon to view very precise a representation of internal anatomy from pre-operative scan modalities. Scan can be combined with an anatomical atlas producing 3-D patient model and the model of devices like artificial heart or valve can be add for treatment planning prior the operation. For surgery robots (telemanipulator) the following distinct phases can be recognised:

- Pre-operative planning: The optimal strategy is defined based on 3-D computer model.
- Robot assisted intervention: A calibration routine brings robot, patient and image system to common frame of reference – e.g by anatomical (or artificial) landmarks.
- Feedback and re-planning: The robot starts the work under supervision of surgeon.

Sensor information assures that the anatomy is as expected and stored by a model in computer. If deviations occur the surgeon asked for a revised strategy, or for permission to continue.

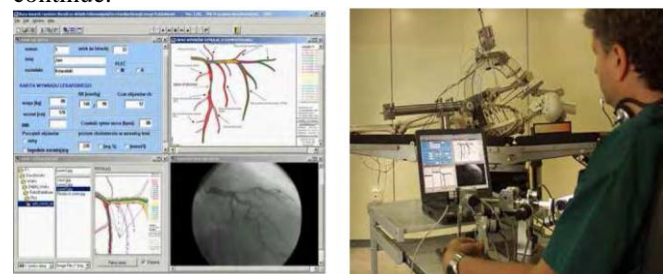


Figure3. Intelligent voice control Database and Advisory system

Currently used cardiac surgery robots fulfill the function of manipulators, which main task is to detect and scale up or down the surgeon hand motions and precisely translate them to the movements of robot's arm equipped in appropriated tools. The basic advantages of cardio robots are safe, reliable and repeatable operative results with less patient pain, trauma and recovery time.

The main issues of computer simulation support of surgery robot:

1. The operation planning – Based on diagnostic data (images, pressure and flow signals, etc.) computer and physical models can be created. In vitro simulations performed on them, may be used to find the optimal way of operation (the joint point localization, the graft selection). Prepared report can be presented to surgeon as a hint for robot choreography planning. This stage also should include: input port localization on patient skin, the type of tools and the way of taking and preparing the graft branch.
2. Advisory and control system – During the operation, diagnostic image from various sources (data base, diagnostic device) can be called by surgeon and superimposed on real operating image to localize the optimal place for CABG connection. Also the simulated or real taken from previous operation recorded in database effect of particular way of connection could be obtained (Fig. 3).

### V. ROBIN HEART

Robin Heart is the name of the family of several robots that have been designed and constructed by the Foundation for Cardiac Surgery Development in Zabrze since 2000 (Fig. 4).

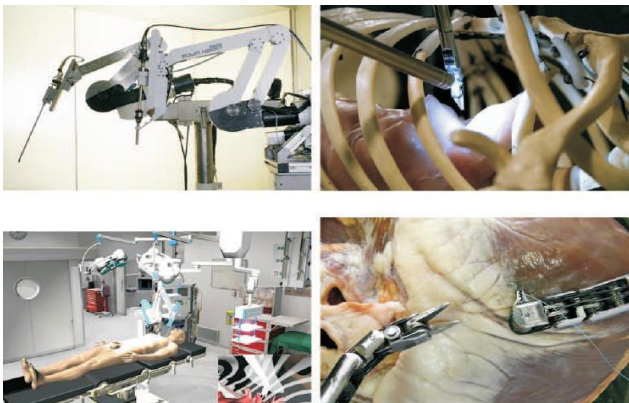


Figure4. Physical and Computer model

The outcome of interdisciplinary works is presented by several models and prototypes that differ, for example, in the concept of control and working mode at the operating table. The robots have a segmented structure, which allows to set them up for different types of operations. The cardiac surgery robot is a copying tele-manipulator that consists of two or more arm tools and one camera-holding tool. The working end of the tool affixed to the arm performs different tasks (gripping device, scissors, and coagulation knife). The kinematical structure of the manipulator consists of the arm (positioning) and the cluster (orientation of the tip). The supervision and control is achieved mainly by means of visual observation and the movement actuator in the control console. The master console consists of 2-dimensional monitor where the surgeon views the image; foot pedals to control electrocautery, instrument/camera arm clutches, and master control grips that drive the servant robotic arms at the patient's side. The Robin Heart Shell console is

equipped with a consulting program that makes it possible to obtain all patients diagnostic information during the operation, as well as elements of operation planning on the screen. The virtual operating theatre introduced in our laboratory allows surgeons to train some elements of an operation, check the best placement of the ports in order to avoid internal collisions. Exhausted by 3-D visualization, this system can be helpful in planning of an operation on a given patient. The mile stone of the project was an animal experiment, carried out in January 2009 (Fig.5-6). The operations were performed on pigs at the Centre of Experimental Medicine, the Silesian Medical University in Katowice with the assistance of cardiac surgeons (Romuald Cichoń, Joanna Śliwka, Grzegorz Religa, Michał Zembala).

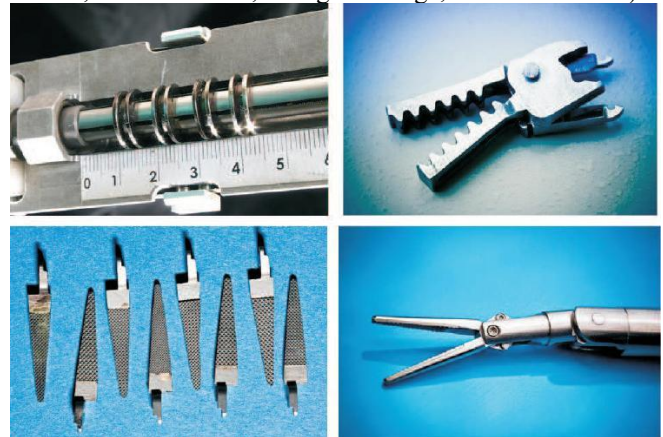


Figure5. Tools

In the course of the experiments our surgeons controlled the robotic arms from the console placed in a separate room next to the operating theater. The control handle has several buttons which are activated after pressing the pedal. Thus, it is possible to simultaneously control the position and the functioning of the tools and the endoscopic camera. Robin Heart system experiment carried out on pigs allowed to verify many aspects of very complex project and was the source of hints for future development. In the course of the animal experiment the surgical task achieved in the abdominal space was cholecystectomy, and in the chest and heart; the repair of heart valves (with extracorporeal circulation) [11].



Figure6. The animal Experiment



VI. CONSTRUCTION OF ROBIN HEART

At the starting point of RH project the multidisciplinary team from several scientific centers in Poland was setup. The group of basic constructors both of mechanical and electronic part was mounted (fixed) consists of Leszek Podsedkowski, Krzysztof Mianowski and the authors of presented paper.

A. ROBIN HEART 0

Robin Heart 0 was built in 2002 (Fig. 7). Its spherical structure consists of the parallel mechanisms displacing the axis of the second DOF into position outside the whole mechanism. 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 180°, 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.



Figure7. Arms of Robin Heart 0

It comprises the parallel mechanism system. The range of rotation angle is 150°. 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. The rotational movement is further transferred onto the system of two parallel mechanisms connected with joints and two fragments of the gears. 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.

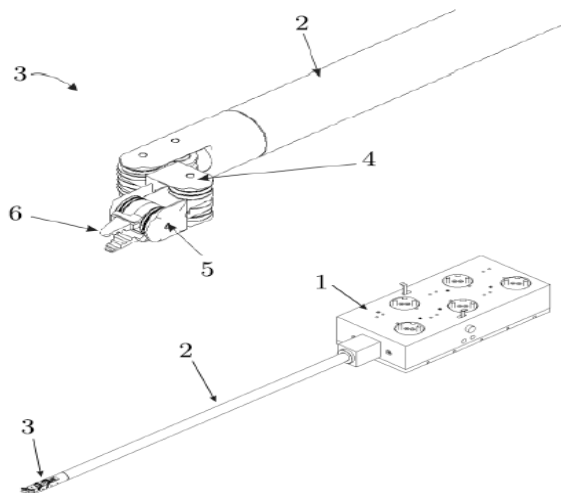


Figure8. The tool of Robin Heart 0

The tool applied in RobIn Heart 0 is presented in (Fig. 8) 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.

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. 9) allowing to reach any orientation including “backward” work.

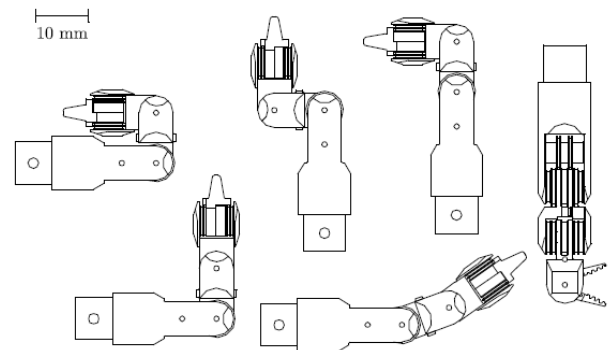


Figure9. Manipulate ability of the Wrist

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).

B. 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. 10). 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.



Figure10. 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  $120^\circ$ , the structure of the parallel mechanisms was simplified, which resulted in high compactness of the 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. Decreasing mass of the wrist drive has been obtained by replacing modeler 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. 11).



Figure11. Tool of Robin Heart 0(diameter 10mm) and Tool of Robin Heart 1(diameter 8 mm)

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

### C. ROBIN HEART 3

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. 12).

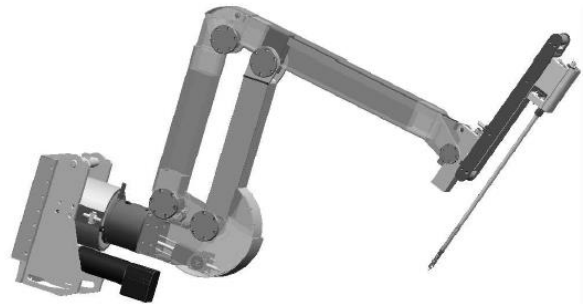


Figure12. Robin Heart 3

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 and the cylindrical gear with clearance elimination system. In the linear drive (3<sup>rd</sup> 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 [12].

## VII. HARDWARE

The master tool has movement sensors mechanically coupled. These sensors are connected to a data acquisition card and then to a USB port of a PC, as seen in (Fig. 13).



Figure13. Hardware of the Evaluation System

### A. Configuration of robot

The Robin Heart master tool, shown in (Fig.14), is a mechanical development in aluminum with 4 joints: 3 of them rotational and 1 of them prismatic. Each joint includes a sensor to detect the position of the master according to surgeon's hand movement.

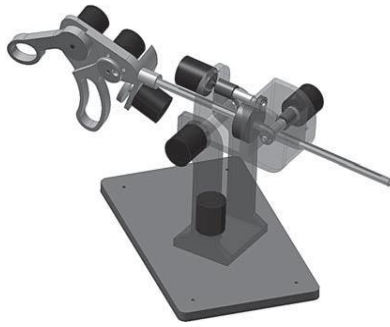


Figure14. Robin Heart Master Tool

The developed model took into account that even though the system has seven degrees of freedom (DOF) only four of them are considered given because the movement of the grasper does not affect the final position of the master. The forward kinematic analysis of the master system using the Denavit Hartenbergs' algorithm was presented in a previous work [3] obtaining the relations presented in (1), (2) and (3):

$$X = d^3 \sin(q_2) \cos(q_1) + L_2 \cos(q_2) \cos(q_1) \dots\dots (1)$$

$$Y = d^3 \sin(q_2) \sin(q_1) + L_2 \cos(q_2) \sin(q_1) \dots\dots (2)$$

$$Z = -d^3 \cos(q_2) + L_2 \sin(q_2) + d_1 \dots\dots (3)$$

**B. Sensors**

The sensors used in the Robin Heart master are optical encoders. Each of these sensors allow for the measurement of rotational movement of each axis. The application of encoders is found generally in control movement systems. There are two kinds of optical encoders: incremental encoders and absolute encoders. Robin Heart system works with incremental encoders.

Absolute encoders generate a unique code for each position, generally using the gray code. In this case, it is possible to know the final position if the initial position is unknown. Incremental encoders, although they do not determine absolute position, have greater resolution and are generally more affordable. One incremental encoder has 3 signals, A channel, B channel and Index. They are used to gauge the position of the encoder. There is a 90 degree displacement between A signal and B signal. If A leads B, then the movement of the encoder is in one direction and, if B leads A, then the movement of the encoder is in the opposite direction, as seen in (Fig.15). The Index channel indicates a reference position.

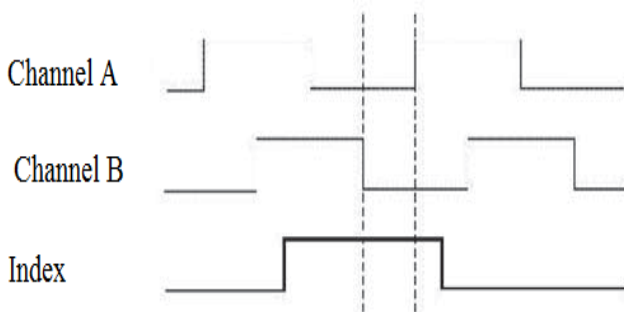


Figure15. Wave form of Encoder

Incremental encoders (SIMEX reference GI328.060422) were used for this project.

**C. Data acquisition card**

The card used in the project was a USB 6009 by National Instruments, (Fig.16)



Figure16. Data acquisition card USB 6009

This card has the advantages of being small, highly portable, affordable and multifunctional. Some characteristics are [5]:

- 14 bits of input resolution
- Maximum sampling rate of 48 KS/s
- Input range of • ±1 to ±20
- Output resolution of 12 bits
- Output rate of 150 Hz
- Output range of 0 to 5V
- 12 digital I/O lines
- 1 counter of 32 bits
- Trigger digital

As it is possible to see in these specifications, this card is not specialized in reading encoders and only has one counter, as a result, it was necessary to use the analog input of the card, utilizing 10 V for the sensors and reading A channel and B channel for each encoder. So, the system works taking into account the limit frequency of the card [13]. The connection of the system can be seen in (Fig.17).

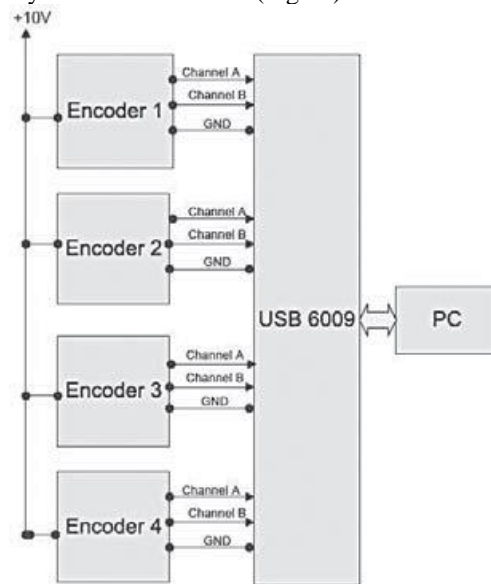


Figure17. Connection of the System

**VIII. SOFTWARE**

**A. Data acquisition**

The data acquisition was done using Lab View to receive the encoder signals. The frontal panel of this software has the following parameters of configuration:





1) *Physical channels*: it is necessary to choose the device, in this case, the USB 6009 card and the channels in which are connected signals A and B of each encoder. If the computer has more than one device by National Instruments installed, it is necessary verify which device is the USB 6009, with help of MAX, an additional program to facilitate the interface with the user.

2) *Maximum and minimum values*: These are the extreme values of voltage in the read signal. The encoders work between 10-30 V, but the card can only support up to 10 V; for that reason, the system was configured at 10 V as the maximum value and a small negative number as the minimum value.

3) *Input terminal configuration*: This parameter is to determine if the connections in the card are referenced at ground or if it is a differential connection between the inputs. This application is referenced at ground. Additionally, there is one parameter of time:

4) *Sample rate (Hz)*: According to the specifications of the card, it can read at 48 KS/s. Nevertheless, this value must be divided equally among the number of channels. In this case, there are eight channels, so the maximum sample rate possible is 6000Hz. It is necessary to create a configuration of falling edge detection, because the algorithm needs to know values to determine the falling edge of the signal, the moment when the signal changes from high level (1) to low level (0). Since the high or the low value voltages depend on the input range of the signal, it is necessary to create the following parameters for doing the configuration:

5) *Limit on*: This is the value of the signal on high. The limit on should be 10 because the development operates at that voltage, but because the signals are not perfect, a limit on value of 8 was assumed.

6) *Limit off*: It is the value of the signal on low. In theory this should be zero, but considering that these kinds of signals are not perfect, a value of 2 was placed in this parameter for this application. Finally, there is a parameter for the pulse counter

7) *Up/down*: This parameter is put in the middle of the range of the signal. In this case, the range is from 0 to 10V, so Up/down was set at 5. Internally, the software works according to the block diagram of (Fig.18).

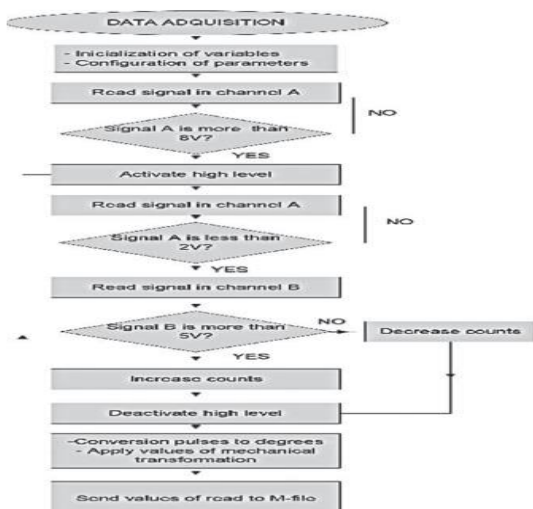


Figure18. Flow chart of Data Acquisition Implemented in LabView

All the readings are saved in one \*.m file in order to analyze them in Matlab and use them for the model verification and the creation of trajectories.

## IX. TESTS OR ROBIN HEART EXAMINATION AND EVALUATION

The goal of surgery robot testing program is evaluation of whole system efficiency. Some parts of Robin Heart testing procedure include classical examination of telemanipulators with additional requirements for medical devices. After preliminary tests and elimination of mechanical and control defects we are preparing to perform tests on animals in condition of operational room and as a last step clinical application is planned. On the initial stage of mechanical system assumptions the analysis of maximal forces needed for standard surgery procedures was performed. During tests carried out by means of dynamometric stand on fresh pig hearts from basic surgery actions like: sewing, cutting, knot tying. The maximal force (18 N) was applied in case of scalpel cutting. Based on these results the load for robot arm tool tip was designed.

### A. Tests of Robin Heart 0&1&2 systems

#### 1). Mechanical system examinations.

Mechanical tests included:

- Study of the arm stiffness with tool mounted
- repeat tests of tool tip positioning for chosen directions
- Measurements of forces between tool tip and surrounding tissues
- Tests of tool tip velocity for different movement directions
- Tests of absolute accuracy of tool tip positioning in the coordinates of arm base
- Hysteresis tests of tool tip positioning

Practically verified resolution of tool tip for every direction is  $\pm 0.02$  mm. The accuracy of operator tool trajectory mapping is about 0.3 mm. Preliminary examinations showed the mechanical hysteresis equal 0.03 mm (for RH1) and 0.02 (for RH2). Stiffness coefficient in this configuration was about  $4.85 * 103$  N/m (RH0),  $2.86 * 104$  N/m (RH1) and  $5.5 * 103$  N/m (RH2).

#### 2). Tests of control and driving systems.

During test phase of project realisation following basic preliminary assumptions were positively verified. The basic function of telemanipulator like mapping of user interface tool movements into arms movements with such options like scaling and low pass filtering was implemented and tested (Fig.19) Tests of control systems computational efficiency acknowledged the algorithm sampling frequency FS equal or above the 1 kHz. ( $TS \leq 1$ ms):

- FS = 1 kHz for Robin 0&1
- FS = 1.4 kHz for Robin 2 robot.

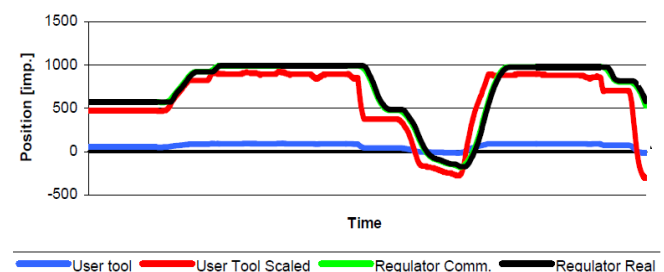


Figure 10. Trajectory of operator handle (original and scaled) and trajectory of corresponding motor (commanded and real) [14].

Movement scaling as well as the effect of low pass filtering (trajectory smoothening)

## X. CONCLUSION

However, this is just the Beginning. Robotics technology can blur the Boundary between Surgeon and Specialist. 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. Endoscopic microsurgery is difficult to perform with standard hand held instruments but till now robotically assisted did not solve all the problems. In most surgery procedures assisted by robots, only part of these kind of operation are carried out using robot. In this connection the strategy of RH project plans to prepare the family of robotic or semi-automatic surgical tools, which usage could be planned according to required functionality. RH clients will be able to choose both Master tool interface and expert system efficient and comfortable for them. The surgery planning can be carried out using 3D virtual operation room. Efficiency of using robotic equipment in an endoscope procedure significantly depends both on a proper tools geometry optimization and a correct surgery procedure planning. Accurate arrangement of setting up the robots arm with reference to an surgery table, positioning the trocars location in a patient body and right choice of a correct tools, makes the surgery procedure much more safe and harmless. Using a virtual reality technology to plan all those important steps, increases efficacy of a noninvasive surgery methods and helps to verify a benefits of using robotic systems in a various surgery treatment.

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- 2) Secured 3<sup>rd</sup> prize in 4<sup>th</sup> National level Technical Paper Presentation, "Futurizm13" held on 1<sup>st</sup>-2<sup>nd</sup> March 2013 on "Piezoelectricity (Renewable Energy System)" at PDEA College of Engineering, Manjari (Bk.), Pune, Maharashtra, INDIA.

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