THE INTERNATIONAL JOURNAL OF MEDICAL ROBOTICS AND COMPUTER ASSISTED SURGERY
Int J Med Robotics Comput Assist Surg 2006; **2**: 36–44.
Published online 6 March 2006 in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/rcs.67

ORIGINAL ARTICLE

Polish cardio-robot 'Robin Heart'. System description and technical evaluation†

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†No conflict of interest was declared.

Accepted: 11 January 2006

Abstract

Background This paper presents the mechanical structure and control system of the Polish cardio-robot Robin Heart (RIH).

Methods The Polish project with cardiac surgery robots started in 2000. It was supported by the team from the Foundation of Cardiac Surgery Development, Zabrze, in cooperation with research centers in Lodz and Warsaw. So far three prototypes, RH0, 1 & 2, of the Robin Heart robots family have been designed, constructed and tested. In addition many diagnostic systems have been constructed to aid with the assessment of robot performance.

Results The main focus of this article examines the technical evaluation of our prototypes, based on laboratory test results of both the mechanical and control aspects of the telemanipulator systems.

Conclusions The presented test results of both mechanical and electrical aspects of Robin Heart telemanipulator systems, show significant progress both in a mechanical and control viewpoint, along with an improvement in the characterisation of the test parameters. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords surgery robots; minimally invasive surgery; telesurgery

Introduction

Nowadays surgeons try to carry out most operations in a less invasive way, through small openings in the body of the patient, because wide opening of the thorax introduces considerable injury of the tissues and causes a risk of infection and various complications (1,2). The replacement of traditional laparoscopic surgery tools with telemanipulator systems allows the introduction of some advantages resulting from high-level technological solutions. The scaling of surgeons' hand movements, tremor elimination and a comfortable work place for the surgeon guarantee more precise movements of instruments inside the body and, as a result, improves the ergonomics and efficiency, as is clearly visible, for example, during long (several hours) surgical operations. Supervision is by optical observation via a voice- or manually controlled endo-camera (two or three-dimensional, 2D or 3D). American cardiosurgical robots have been produced by two companies, currently merged, Computer Motion® Inc.(Goleta, CA), and Intuitive Surgical® (Mountain View, CA) and were first used clinically in Europe (3). The world's first mechanical surgeon's assistant, a voice-controlled endoscope positioner, AESOP 1000 (auto-endoscopic system for optimal positioning), was introduced by Computer Motion® in 1994(4). In January–May 1998 a French team in Paris and a German group from Leipzig performed the world's first endoscopic operation, a single coronary bypass and mitral valvuloplasty, using the da Vinci (Intuitive Surgical®) telemanipulator. In summary, about 1000 surgical and endo-camera robots have been installed in clinics, including Katowice, Poland (5) and have so far been used for more than 100 000 minimally invasive procedures across a broad range of surgical applications, such as general, gynaecological, spinal, urological and cardiothoracic surgery.

Robin Heart – Polish robot for cardiac surgery

In 2000 the Foundation for Cardiac Surgery Development (FCSD) in Zabrze began its project for the realization of the prototype for a robot useful for cardiac surgery. Over 3 years the multidisciplinary team, including medical and technical specialists, prepared two families of robot prototypes named Robin Heart.

The basic idea of the manipulator Robin Heart consists of mechanisms for realizing fixed in space 'constant points', and consists of two closed kinematic chains (6,7). The first loop is in fact a typical parallelogram mechanism, used as a transmission mechanism, coupled with the second one, a realized inverse mechanism. By special connection of the two rotations, coupled by a constant angle internal link, the mechanism can change the external angle to approximately 150°. In the version Robin Heart 0 (RH0) shown in Figure 1, the first degree of freedom (DoF) is driven by a brushless electric motor integrated with a harmonic drive gear. The second (range up to 150° doubled system of parallel mechanisms) and third DoFs (the parallel mechanism eliminates the necessity of using a linear slideway) are driven by brushless motors, roller screws and a system of strings. This construction makes possible rapid and uncomplicated disconnection of the drive part of the bunch from the manipulating part. The separable part contains no elements requiring lubrication. In the bunch part, five independent drives and the string drive give three DoFs, enabling any orientation to be obtained in the workspace. The fourth DoF makes possible the opening and closing of the jaws of the tool and the fifth one (called 'the elbow') is redundant and increases manoeuvrability, enabling the avoidance of obstacles and operating 'backwards'. In the pre-prototype version, the diameter of the bunch is 10 mm. For the drive, servomotors with DC electric motors and no-clearance gears have been used.

The RH0 has been tested and the new prototype has been designed. In the prototype Robin Heart 1 (RH1, Figure 2) a diminution of the mass and size of the tools driving block, an increase of the stiffness of the arm

Figure 1. The prototype of the tool arm of the Robin Heart robot: the Robin Heart 0 arm

Figure 2. The prototype of the Robin Heart 1 tool arm

and rearrangements of the carriage of the drive were introduced. As a result, the driving block has dimensions $46 \times 48 \times 90$ mm and a five-fold smaller mass (0.4 kg). Additionally, a project on a so-called 'penknife' universal end, having more than one working tool element, was executed. In RH1 the diameter of the bunch was decreased to 8 mm.

Robin Heart 2 (RH2)

We decided also to create a competing model of robot arms, a relatively light construction mounted directly onto the operating table. The basic idea of the manipulator consists of mechanisms realizing a 'constant point', consisting of two closed kinematic chains. The first loop is in fact a typical parallelogram mechanism, used as a transmission mechanism, coupled with the second loop, a realized inverse mechanism. By special connection of the two rotations coupled by a constant-angle internal link, the mechanism can change the external angle to approximately 150°. The advantage of this solution is a straight, aesthetic, compact and tight construction giving high functional efficiency in operating action. The arms are mounted onto the table using a special folding console

DOI: 10.1002/rcs

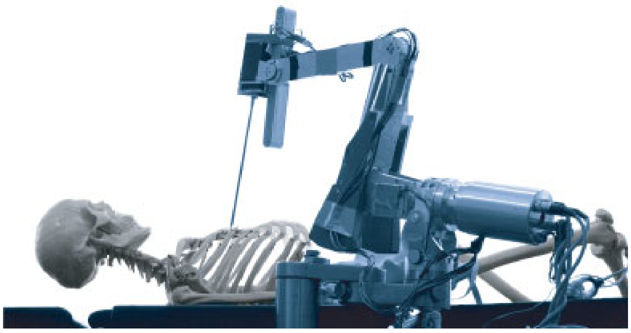


Figure 3. The prototype of the Robin Heart 2 arm, equipped with modified (semi-automatic) laparoscopic tool

from two passive arms and columns. The RH2 manipulator (Figure 3) has a very good and relatively large working space, in which the surgeon can select a small subspace with very good isotropic kinematic properties for the manipulation of objects with good positional accuracy. The initial tests were carried out in a bio-cybernetics laboratory.

The manipulator is driven by brushless DC engines. The control system of RH2 is an original design, based on the current top technological solutions – microcontrollers dedicated for motor control (Microchip® PIC® family) and computationally powered digital signal processors (DSPs) organized in a net of modules reading the data from the operator tool, processing signals (with additional options, e.g. scaling, trajectory filtering) and creating conditions for driving systems (Proportional, Integral, Differential (PID) controllers).

Comparison of robots

The mechanics of existing cardiosurgical robot constructions consist of a mechanical arm with replaceable laparoscopic tools specialized for different functions – cutting, sewing, removal of tissues, etc. Tools introduced into the patient's body can possess different numbers of degrees of freedom (DoFs). A suitable number of DoFs at the tool's 'wrist' makes possible the execution of different types of operation. In robot constructions so far described these are as follows. In the da Vinci (DV) robot the bunch is about 8.5 mm in diameter and possesses three DoFs. In the Zeus (Z) robot the specification is dependent on the model: for bunch diameter 3.9 mm there are two DoFs and for diameter 4.9 mm three DoFs. Both RH0 and RH1 have four DoFs, including an additional joint for working backwards. In RH0 the diameter of the tool is 10 mm, while in the new RH1 it is 8 mm. For RH2 there are currently simply two DoF tools; this model is dedicated especially as a base for an endoscopic camera.

The second element of the telemanipulator is the arm, which assures the possibility of translocating the working end of the tool inside the patient's body while maintaining one constant point – the passage through the patient's skin (the so-called 'port'). In the described constructions, two methods, kinematic and passive, of constant point creation in the working space are applied. The passive method is modelled on the classic laparoscopy solution. The point of passage of the tool through the patient's body (i.e. the point of support of the tool) can be treated as a 4 class joint with two DoFs. To fix all six tool DoFs, the robot arm should have four DoFs. Three of these are achieved by the positioning of the external end of the tool. In the Zeus arm it is realized using the Selective Compliance Assembly Robot Arm (SCARA) type of manipulator construction. To obtain proper manoeuvrability it is necessary to use two non-driven joints (a kind of Cardan universal joint) at the point of connection of the robot arm with the tool. The next DoF, responsible for turning the tool in relation to its axis, is usually driven by a motor. The disadvantage of this solution is loading of the tissue near the port as a result of supporting the tool during action. The flexibility of the tool is also increased.

In summary, the Z arm possesses three DoFs which, together with the DoFs of the tools, gives five or six DoFs depending on the kind of tool used. In telemanipulator DV, RH0, RH1 and RH2, the kinematics solution was used for realization of the constant point condition of working. In the DV robot the total number of DoFs is six. In RH0 and RH1 there are seven DoFs because of the tool with one additional joint.

The next important problem is power transmission into the tools. In the constructions described this is realized using strings or followers. In the DV each DoF is driven via strings. The range of movement of individual joints of the tool is considerable – usually ±90° for every joint. The strings pass through rollers along the whole length of the telemanipulator arm. The motors are placed at the base, which to a considerable degree determines the construction of the arm. Due to the considerable length of the thin strings and their extensions, continuous inspection and adjustment is required before every operation. If a string breaks, the arm is useless for further manipulation, which is the disadvantage of this type of construction.

The type of transmission used in the Zeus robot has limited possibilities of driving a large number of successive DoFs. Fundamentally, two movements can be obtained: alterations of the pitch of the tool and its closing or opening. The range of movement is also very limited: ±40° for pitch and 20° for opening of the tool. However, it possesses some undeniable advantages – the small diameter of the tool (3.9 mm) and high reliability.

In the preliminary prototype RH0, string drives were used similar to those of the DV, but for shorter sections; the strings are only 40 cm long. Because the endoscopic part of the tool is separable, the breaking of driven strings does not cause immobilization of the robot. A change of tool to a new one will permit the operation with the robot to be finished. An increase of the mechanical properties and durability of this element has been achieved in RH1. In this model hybrid drive follower strings are applied and the longest strings were shortened to about 10 cm.

The new compact construction of arm, together with smaller motors, is the reason why the new arms are lighter and occupy a smaller area above the operating field. The most space is occupied by the DV robot, in which three arms are situated on a common massive column.

Control system of the telemanipulator

The main idea of the control system is common to all the cardiosurgical systems described, including the Zeus and daVinci systems. The main task of the master–slave teleoperator is reliable mapping of the surgeon's hand movements (setting of position/velocity/acceleration of other physical quantities) onto the movements of the tool arm, through calculation of control signals for its motors.

The technical requirements for the Robin Heart surgical telemanipulator control system were:

- Frequency of updating signals in the main control loop for translating the master arm commands into the slave arm movements, which ensures fluent work, should be at least 1000 Hz.
- Satisfactory precision of surgery procedures, taking into account the small sizes of anatomical objects (e.g. 1 mm diameter of coronary vessels) should be guaranteed by positioning accuracy and resolution of at least 0.1 mm.
- Delay between the master and slave arm movements should be lower than the acceptable limit: $T_{\mathrm{DEL\_MIN}} <$ 50 ms.
- Possibility of scaling the movements between the operator and the arm with surgical tool.
- Introduction of the surgeon's commands, apart from position (by means of master arm), by other forms of communication with the system (e.g. voice control), to increase the comfort of the user interface.
- Elimination of the surgeon's hand tremor.
- Optional possibility of 'mirror' movements correction.
- Hardware and software movement limit detection on a particular axis.
- Communication with host computer (RS, Ethernet) to change work parameters and monitor the current state of the system.
- Optional introduction of force feedback, with the possibility of scaling the sense of force (or others: audio-visual, thermal or mechanical vibrations) passing to the operator.
- Optional software implementation of movement sets, realizing base surgery procedures in semi-automatic mode (directed and supervised by the surgeon), is planned.

A few different concepts of hardware and software were analysed to obtain the best result: a system easy to develop and debug and reliable during normal operation. Two technical solutions were designed, developed and put into practice during the project realization:

- A system based on a VME bus equipped with specialized cards for motor control, working under real time operating system OS9 (PEP®, Modular Computers).
- Systems of PID regulators working in a net, based on microcontrollers specialized for motor control, supervised by a DSP unit. This type of hardware/software solution was also applied in the Zeus and daVinci systems.

Advisory system: planning for robotically assisted surgery

Preoperation planning involves several research efforts using computer and physical models, performed to achieve an optimized surgical effect by the appropriate choice of methodology, materials, devices and techniques.

Modern medical imaging methods, such as computed tomography (CT) and nuclear magnetic resonance (NMR), enable the surgeon to view very precisely a representation of internal anatomy from preoperative scan modalities. The scan can be combined with an anatomical atlas, producing a 3D patient model, and models of devices such as an artificial heart or valve can be add for treatment planning prior to the operation. For surgery robots (telemanipulators) the following distinct phases can be recognized:

- *Preoperative planning*. The optimal strategy is defined based on a 3D computer model.
- *Robot-assisted intervention.* A calibration routine brings robot, patient and image system to a common frame of reference, e.g. by anatomical (or artificial) landmarks.
- *Feedback and replanning.* The robot starts to work under the supervision of the surgeon. Sensor information assures that the anatomy is as expected and is stored by a model in the computer. If deviations occur, the surgeon is asked for a revised strategy or for permission to continue.

For medical applications, coordination between diagnostic images and off-line intervention planning and real execution is very important. Many problems still remain unsolved for soft tissue surgery, where deformations may occur. The navigation and guidance of the instruments depends greatly on the skill of the surgeon, who has to combine his intra-operative views with the information extracted from the preoperative images. The system currently developed in our laboratory allows for parallel display of four pictures on the monitor, taken from independent sources (e.g. a real view of the operative field, next to diagnostic images or preoperation simulation results).

To plan the whole surgery procedure by means of physical and mathematical models, particular objects belonging to field of operation should be characterized in this domain. We propose an original solution of a remote-control manipulator for cardiac surgery with a computer-based advisory system (8,9). Information gathered in the prepared database may be used by the surgeon as an on-line expert system to support him in decision making. A first step is to prepare the robot-assisted surgery related to both computer and physical models of a particular type of operation. Based upon preoperation cardiac surgery simulations, the optimization of cardiac surgery procedures can be established. The implementation of *in vitro* simulation for surgery procedure has been performed. As a result of physical and computer simulations (ProEng®, Fidap® systems), surgery modification of biological system effectiveness with use of the different surgical techniques is studied. As a result of research connected with operation planning, optimization of the port location and choreography of the robot arm for these cases is performed. Based on the effects of this work, the control algorithm for cardiac surgery robot is proposed.

In this part of the robot system we have so far been working on two main issues:

1. *Planning the operation.* Based on diagnostic data (images, pressure and flow signals, etc.) computer and physical models can be created. *In vitro* simulations performed on these may be used to find the optimal method of operation (the joint point localization, the graft selection). The prepared report can be presented to the surgeon as a guide to step-by-step choreography planning of the robot. This stage also should include input on port localization on the patient's skin, the type of tools to be used and the way of taking and preparing the graft branch (10).
2. *Advisory and control system.* During the operation, diagnostic images from various sources (database, diagnostic device) can be called by the surgeon's voice and superimposed on the real operating image to localize the optimal place of current surgery activity (e.g. Coronary Artery Bypass Graft (CABG) connection). Also the simulated or real image taken from a previous operation and recorded in the database, showing the effect of a particular method of connection, could be obtained. This intelligent database is shown in Figure 4.

Laboratory testing of the robot

The main goal of the surgery robot testing programme is evaluation of the whole system's efficiency. Some parts of the Robin Heart testing procedure include a classical examination of the 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 under the conditions of the operating room, and clinical application is planned as a last step.

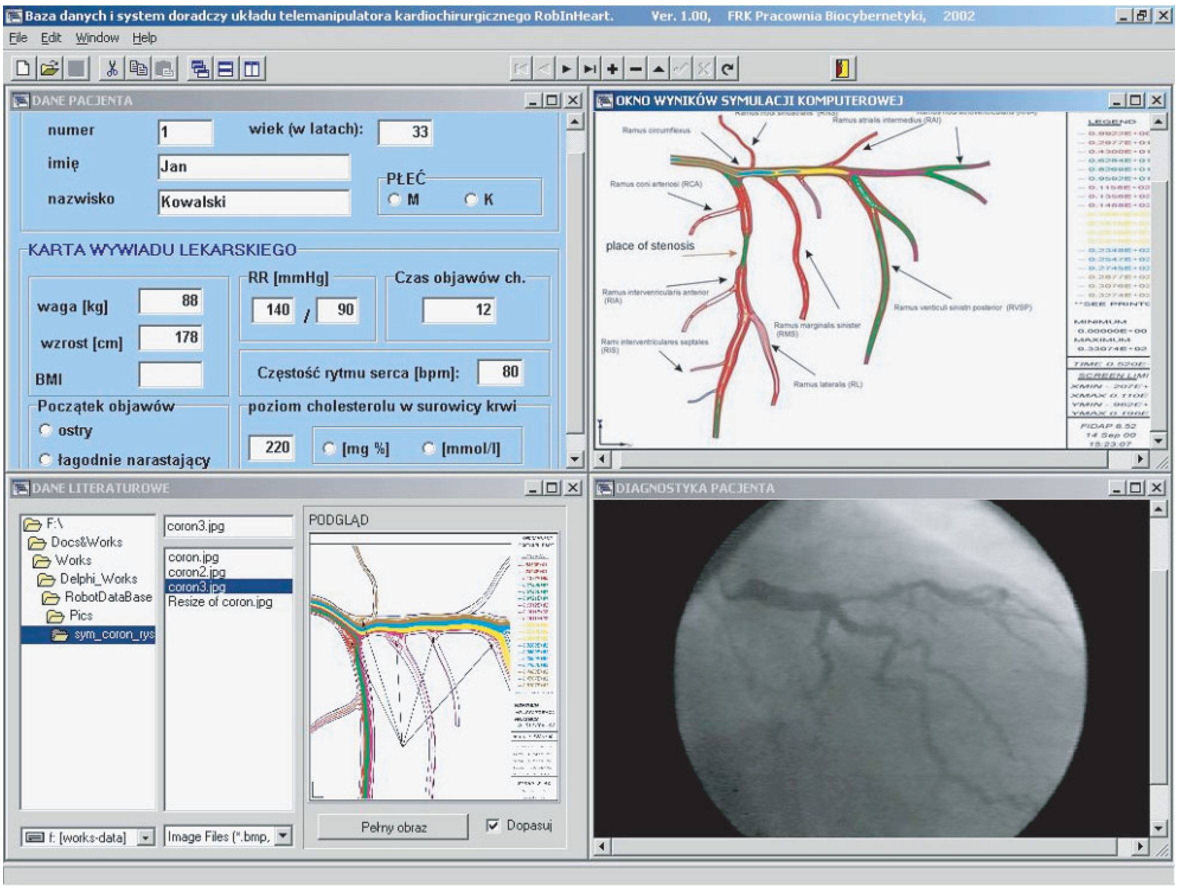


Figure 4. Intelligent voice control database and advisory system

DOI: 10.1002/rcs

In 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 a dynamometric set-up on fresh pig hearts, on basic surgical actions such as sewing, cutting and knot-tying, the maximal force (18 N) was applied in case of cutting with a scalpel. Based on these results, the load form robot arm tool tip was designed.

To standardize the robot tests, we tried to translate the operation on real tissues into actions in a simulation environment, which consisted of an electromechanical system able to create load conditions in the range and dynamics of natural material. The control system for this sophisticated testing set-up is built based on analysis of real data and modelling of the interactions which appear during surgery. Currently we test this system for one degree of freedom, but we plan to extend it to a 3D system in Cartesian coordinates.

The procedure of arm test is following:

1. The tool tip is fixed to the modelled object (during crash tests they only touch).
2. Definition of tested object character (e.g. aorta) by choosing an appropriate procedure.
3. Definition of the robot task.
4. Analysis of the test results.

Thanks to this procedure, we are able to compare robots and their particular parts (mechanics, control system, force feedback) in repeatable, standardized tests.

Testing of the mechanical system

Mechanical tests included:

1. Study of the stiffness of the arm with tool mounted.
2. Repeat tests of tool tip positioning for chosen directions.
3. Measurements of forces between tool tip and the surrounding tissues.
4. Tests of tool tip velocity for different movement directions.
5. Tests of absolute accuracy of tool tip positioning in the coordinates of the arm base.
6. Hysteresis tests of tool tip positioning.

The practically verified resolution of the tool tip for every direction is ± 0.02 mm. The accuracy of operator tool trajectory mapping is about 0.3 mm. Preliminary examinations showed that the mechanical hysteresis was 0.03 mm for RH1 and 0.02 for RH2. The stiffness coefficient in this configuration was about 4.85×10^3 N/m for RH0, 2.86×10^4 N/m for RH1 and 5.5×10^3 N/m for RH2.

Testing of the control and driving systems

During the test phase of project realization, the following preliminary assumptions were positively verified (Table 1):

1. The basic function of the telemanipulator, such as mapping of the user interface tool movements into arm movements, with such options as scaling and low-pass filtering, was implemented and tested.
2. Tests of the control system's computational efficiency showed the algorithm sampling frequency, F_S, to be equal to or above 1 kHz (T_S <= 1 ms): $F_S = 1$ kHz for RH0 and RH1; $F_S = 1.4$ kHz for RH2.
3. Several testing set-ups and systems were elaborated:
   - The complex (embedded) system to evaluate the precision of the mapping of surgeon manipulation into robot arm movement, based on surgeon tool and arm motor trajectories analysis allowed to verify the system resolution as 0.1 mm.
   - The same set-ups allowed us to carry out the hysteresis and repeated movements tests for both arms.
   - The use of technological top semiconductor accelerometer and gyroscope sensors for acceleration and angle velocity measurements opened the new field of study of robot dynamic properties. It

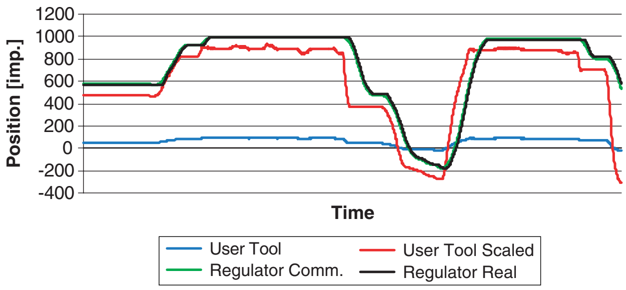


Figure 5. Trajectory of operator handle (original and scaled) and trajectory of corresponding motor (commanded and real). Movement scaling and the effect of low-pass filtering (trajectory smoothing)

Table 1. Test results summary for the Robin Heart systems family

Test type/parameter	Robin Heart 0 (RH0)	Robin Heart 1 (RH1)	Robin Heart 2 (RH2)
Arm stiffness coefficient (N/m)	4.85×10^3	2.86×10^3	5.50×10^3
Mechanical hysteresis (mm)	–	0.03	0.02
Main control loop refresh frequency (Hz)	1000	1000	1400
Max. vibration amplitude on tool tip (mm)	4	1	0.5
Frequency range of vibrations (Hz)	4–6	20–35	30–35

DOI: 10.1002/rcs

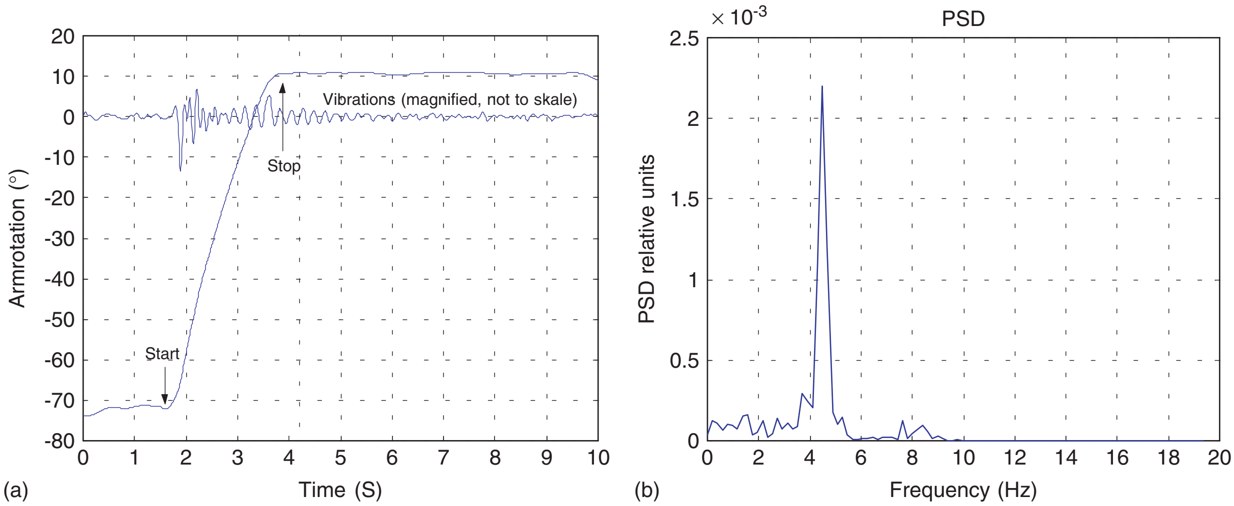


Figure 6. Registered signal and extracted vibration component (A) and power spectral density of vibrations (B) from the accelerometer sensor for Robin Heart 0

allowed us to observe and evaluate many phenomena, e.g. vibration propagation with its frequency domain spectral analysis, which allowed the maximum vibration at a frequency of 5 Hz for RH0 to be found and a more advanced analysis to carried out for RH1, where gyroscope and accelerometer signal processing results are presented on a time–frequency plane correlated with the motor trajectory. The time–frequency plane of vibration energy distribution allows observation of the amplitudes of spectral components together with their localization in the time domain (11) (Figures 6 and 7). This analysis allows the critical moments of robot trajectory generation to be found and these results are the base for control algorithm adjustment.

As it can be seen in Figure 7, the main vibration frequency component for RH0 is located near to 5 Hz and corresponds to the Start and Stop moments of motor movement. For RH1 the vibration frequency components with the highest amplitudes were moved toward a higher frequency range (about 20–35 Hz).

Summary and conclusions

Three prototypes of Polish Robin Heart robots (RH0, RH1 and RH2) for use in cardiac surgery have been created during 2000–2003 at the Foundation for Cardiac Surgery Development, with the cooperation of the robotic centres at Lodz Technical University (Professor L. Podsedkowski's team) and Warsaw Technical University (Dr K. Mianowski's team). Now (2004–2006) the test results of these arms are the basis for work on new telemanipulator systems, including modification of both the mechanical and control parts with a special focus on safety systems development.

The test results of both mechanical and electronic parts of the Robin Heart telemanipulator systems show significant progress in both their dimensions and weight, as well as improvement in characterizing their test parameters.

Vibration measurement and analysis by means of accelerometer and gyroscope sensors has allowed the creation of a model of our systems, as a basis for modification and adjustment of the control system, to compensate as well as possible for the observed negative effects of the arm movements.

Our systems are equipped with a parallely developed surgery advisory system, created on the basis of our long-term experience in using the simulation methods as a decision-making support for surgeons. The research included:

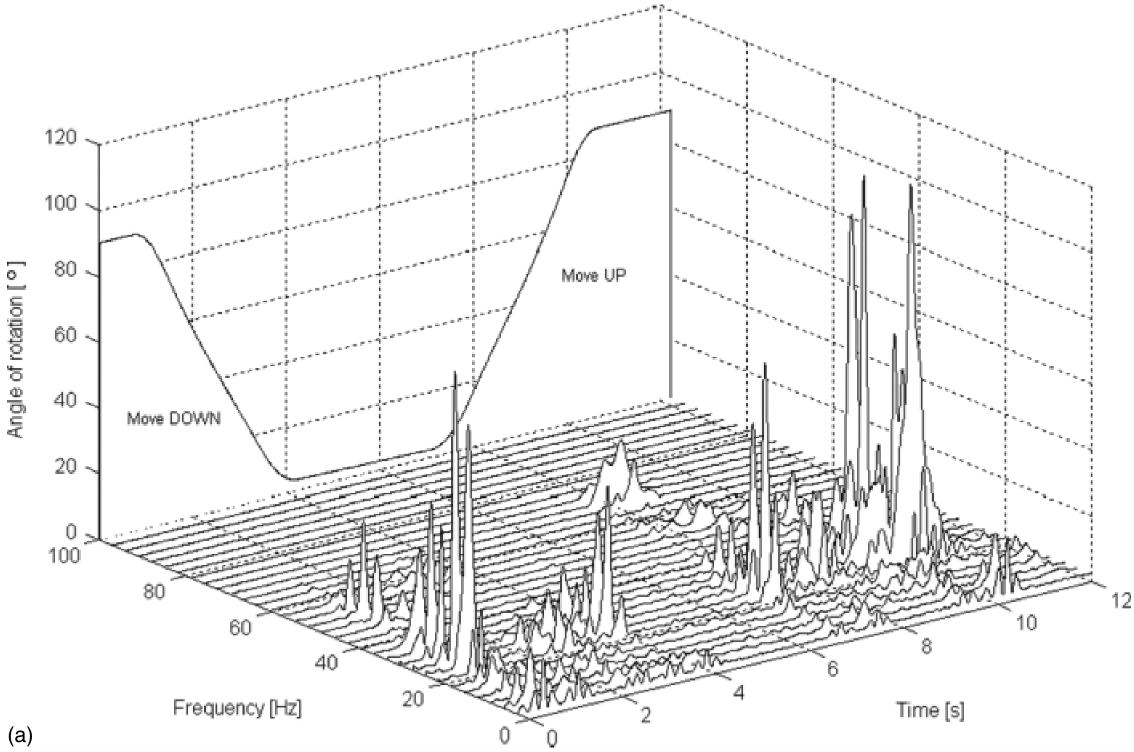
- Strategy planning.
- On-line control.
- Expert and advisory systems for the cardiac surgery robot.

All these activities are carried out with the goal of making the system more user-friendly for surgeon as well as safer for the patient.

The last preclinical robot examination will be the animal test, performed under the specific conditions of the operating room. At the end of 2003 our team received permission from the Ethics Committee of the Silesian Medical Academy to perform the first series of *in vivo* experiments of Robin Heart. The first stage of tests according to our plans will contain the following surgery procedures:

1. Robot-assisted surgery in the abdominal cavity (gonadectomy, bladder excision).
2. Bypass implantation on the beating heart by means of a surgery robot.
3. Extracorporal circulatory procedure using Robin Heart (artificial heart valve replacement).

In the near future, after the preparation of specialized tools, ventricular assistance device implantation by means



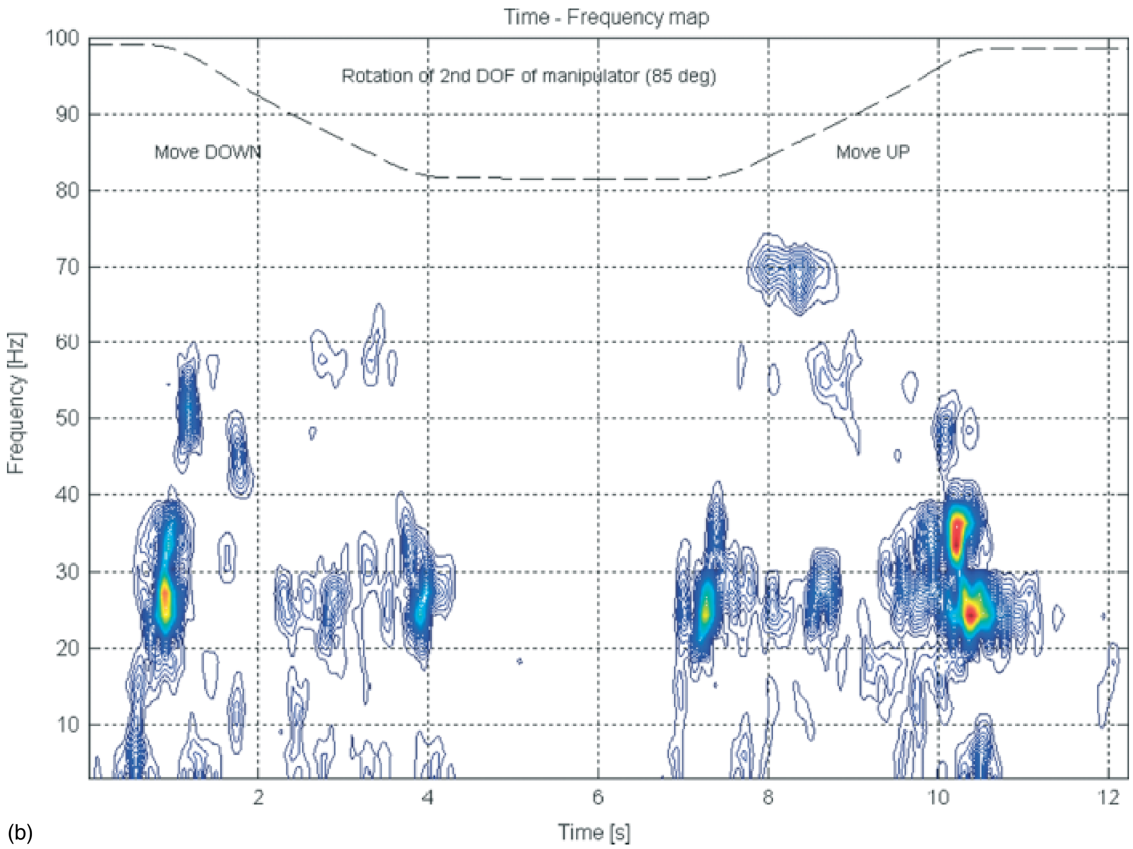


Figure 7. Results of time–frequency analysis of gyroscope sensor signal recording during the 2nd DoF of the Robin Heart 1 up-and-down movement. The main vibration, moved toward higher frequencies (20–35 Hz), can be observed in the acceleration and deceleration phases of the trapezoidal trajectory. 3D time–frequency distribution (A) and corresponding 2D time–frequency map (B)

DOI: 10.1002/rcs

of Robin Heart is planned. We plan to carry out the first animal test of our robot in autumn 2007, the first clinical application of the robotically controlled endocamera arm, Robin Heart Vision, in 2008, and the first clinical operation performed by Robin Heart in 2009.

Acknowledgements

This research was partially supported by the State Committee for Scientific Research (KBN 8 T11E 00118) and the Foundation for Cardiac Surgery Development. We warmly thank our workers, KBN and sponsors for engagement in our project, our numerous collaborators [M. Jakubowski, E. Jezierski, A. Kandora, A. Klisowski, K. Mianowski (chief of mechanical construction of the model Robin Heart 2), S. Midera, L. Podsędkowski (chief of mechanical construction of the model Robin Heart 0 and 1), I. Pawłowski, S. Pietraszek, R. Pruski, A. Wróblewska, P. Wróblewski, Z. Religa (cardiac surgeon, chief of project)] and a considerable number of university students who prepared qualifying and graduate studies and participated in our scientific activities.

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