THE SERVO DRIVE WITH FRICTION WHEELS

Łukasz Frączczak, Leszek Robert Podsędkowski, Marcin Zawierucha

Abstract:

This paper presents the servo drive with force transmission by friction in two DOF. The first section describes some of the problems with surgery robots. In the second section there is shown the operating principle of the friction drive, which is a solution to the mentioned problems. The next section presents the motion control system and the sensors used therein. In the fourth section the author deals with the mechanical solution of the servo drive.

Keywords: *servo drive, friction wheels, surgery robot.*

1. Introduction

Recently technological developments in the field of laparoscopic surgery is an important issue owing to increasing safety as well as patient satisfaction and comfort. For this reason the surgery robots have been introduced into clinical practice. They made it possible to avoid sternotomy, which shortened the recovery time after performed surgery, and minimized the risk of post operative complication.

At present the surgery robots: "Zeus" [1] and "Da Vinci" [2] are used in the clinical practice. However now only "Da Vinci" is still produced. In Poland, some works have been taken to design another surgery robot called "Robin Heart" [3,4,5]. The work was funded by the KBN and Cardiac Surgery Development Foundation in Zabrze. Its prototype was designed and made in the Cardiac Surgery Development Foundation in Zabrze end the Institute of Machine Tools and Production Engineering at the Technical University of Łódź.

At present there are some drawbacks in the use of the surgery robots. One of the most important drawbacks during a cardiac operation is the collision of the robot's arms. This is especially disturbing when does three or fourrobot arms are used. The working spaces of these arms interference one with another. If the surgeon not pay enough attention to the arms position, he often leads them to collision. The working space of the robot's arm depends on the kinematics, which is responsible for the spherical motion of the laparoscope, end the linear drive, which is responsible for the tracts in and out of the patient's body. The robot's arm responsible for the spherical motion of the laparoscope is optimally designed to move the laparoscope with sufficient accuracy. Therefore, it is the only solution that is left is the replacement of the large linear drive with the smaller one. For this purpose a linear drive was developed, which is much smaller than the recently used ones. This linear drive also allows rotation around laparoscope axis. A different approach of this movement was used in the in the design of the servo drive. The solution is based on the use of the laparoscope camera sleeve, or a laparoscope tool sleeve (hereinafter the laparoscope slideway) like a slideway. Then, is only possible solution is a drive, which uses friction, because of the laparoscope slideway is smooth.

Currently, in the literature there are several designed mechanisms, which use friction drive with a two DOF. The most common use of the friction drive is moving the drive linearly and around the shaft axis. This kinematic is used in force simulation mechanism [6], gimbals mechanism [7,8] and ball screw spline model (BNS) [9]. In the BNS, to ensure the accuracy, the shaft have an incision which is unacceptable in the laparoscope slideway. Interesting solutions are: the rolling ring drives [10] and rohlix zero max [11] however, this drive convert only the rotary motion to linear one. In the literature the friction drive is also applicable in more than two DOF drives. One example is the mecanum wheel robot (MWR)[12], which can move in any direction on the plane, it is called holonomic mobile robot.

2. The operating principle

The operating principle of the mechanism is based on the kinematic and force strength motion of the laparoscope slideway, respect to the wheel positioned obliquely to the laparoscope slideway axis (Fig. 1).

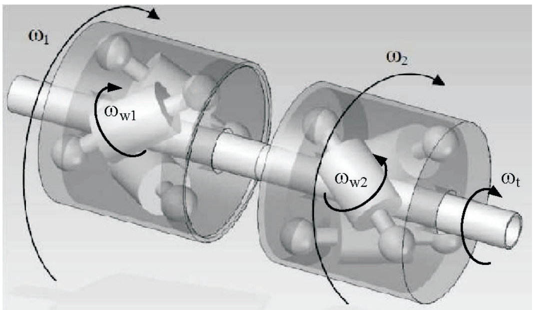

Fig. 1. Idea of the friction drive mechanism.

The drive is transferred through the modules, which are coaxial to laparoscope slideway and rotate around this axis. In this modules there are friction wheels which transfer the drive to the laparoscope slideway.

The velocity distribution at the points of contact of the friction wheels with the laparoscope slideway is shown in Fig. 2. This figure is based on the assumption that there is contact point between wheels and slideway and there is no slippage. Wanted velocities: V_o and V_t. It have to be assumed that $V_{B1} = V_{B2}$. Then after summing of the forces in each axis we get the following equation:

$$V_o = V_{u1} - V_{w1} * \cos\alpha_1 = V_{u2} - V_{w2} * \cos\alpha_2 \tag{1}$$

$$V_t = V_{w1} * \sin\alpha_1 = V_{w2} * \sin\alpha_2 \tag{2}$$

Taking into consideration kinematic and geometric dependences the above presented equations will look as fallows:

$$\omega_0 r_t = \omega_1 r_t - \omega_{w1} r_w \cos\alpha_1 = \omega_2 r_t - \omega_{w2} r_w \cos\alpha_2 \tag{3}$$

$$V_t = \omega_{w1} r_w \sin\alpha_1 = \omega_{w2} r_w \sin\alpha_2 \tag{4}$$

Where:

ω_1, ω_2, ω_{w1}, ω_{w2} - rotational speed respectively module 1 and module 2, then friction wheels at the module 1 and 2.

V_{u1}, V_{u2} - drifting speed at module 1 and 2.

V_{w1},V_{w2} - velocity of the point on the friction wheels surface which represent the linear speed from the rotational speed respectively module 1 and 2.

V_{B1}, V_{B2} - speed which is the sum of the V_{ui} and V_{wi} respectively at module 1 and 2.

V_o - velocity on the laparoscope slideway surface which represent the linear speed of the rotational speed.

V_t - linear speed of the laparoscope slideway.

r_t - radius of the laparoscope slideway.

r_w - radius of the friction wheels.

Setting the ω_{w1} out of (4)and substituting ω_{w1} to (3) gives:

$$\omega_{w1} = \frac{r_t(\omega_1 - \omega_2)}{r_w \sin\alpha_1(\mathrm{ctg}\alpha_1 - \mathrm{ctg}\alpha_2)} \tag{5}$$

Now substituting the ω_{w1} to (4) we get V_t that is equal:

$$V_t = \frac{r_t(\omega_1 - \omega_2)}{\mathrm{ctg}\alpha_1 - \mathrm{ctg}\alpha_2} \tag{6}$$

and substituting the ω_{w1} to (3) we get the ω_t that is equal:

$$\omega_t = \frac{\omega_2 \mathrm{ctg}\alpha_1 - \omega_1 \mathrm{ctg}\alpha_2}{\mathrm{ctg}\alpha_1 - \mathrm{ctg}\alpha_2} \tag{7}$$

Assuming that: $\alpha_1 = -\alpha_2 = \alpha$ the above presented equation gives:

$$V_t = \frac{r_t(\omega_1 - \omega_2)}{2\mathrm{ctg}\alpha} \tag{8}$$

$$\omega_t = \frac{\omega_2 + \omega_1}{2} \tag{9}$$

The consequence of this equation is the independent rotary and linear control of the laparoscope slideway. The most characteristic movement control is when the movement is in one direction. To move the laparoscope slideway rotary the motor shafts must rotate in the same directions with the same rotary speed. From equation (8) we get the result that, there is no linear move, and from equation (9) we get that ω_t is different from zero. In turn, to move the laparoscope slideway linear, the motor shafts must rotate in the opposite directions with the same rotary speed. Then, from equation (9) we have that, there is no rotary move, and from equation (8) we have that V_t is different from zero. The sum of rotary speed and different direction of motor shafts will result in movements in both directions (rotary and linear) of laparoscope slideway.

3. The control system

The friction contact in the servo drive is causing the problem with control system. This is related to the accuracy of friction contact and the possibility of slip between friction wheels and laparoscope slideway. During operation with the use of surgery robots, the uncontrolled slip between driving parts end laparoscope slideway is not allowed, because of health or live of the patient. The restriction of the creation of slip can't be achieved by robot's arm construction, therefore we must ensure this restriction by the automatic control of movement. It is necessary to design appropriate response of the control system, which does not allow to lose control of the laparoscope slideway. For this purpose it is necessary to create cooperation between several measuring systems, which are tracking the movements of both the motor shafts and laparoscope slideway. For this purpose the Automatic Control System (ACS) is realized by two loops. The one (interior) loop is realized by motor drive controllers with measurements of rotary of the motor shafts, the second is realized by tracking the movement of the laparoscope slideway. The second loop is the superior and controls the interior loop, furthermore the external loop have the slip control algorithm. The block diagram is in the Fig. 3.

The main task of the control system is to control the rotation of the motors shafts so that the displacement of the laparoscope slideway is consistent with the set value. The

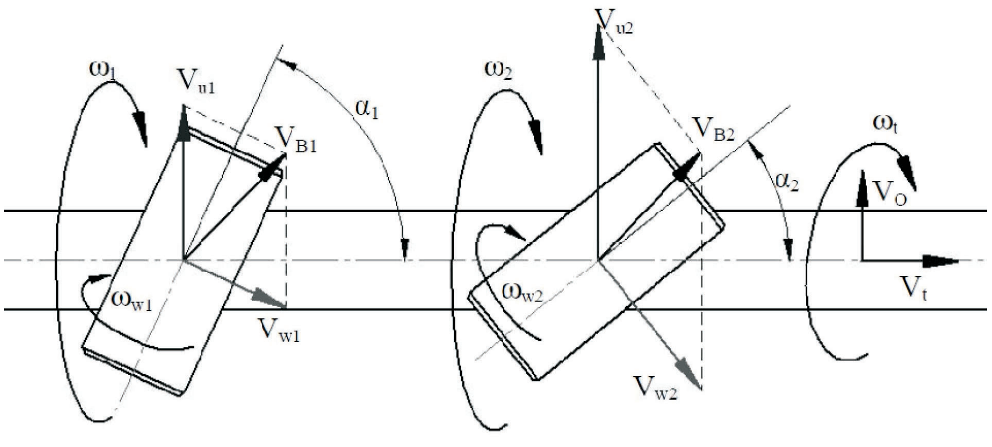

Fig. 2. The velocity distribution at the points of contact friction wheels with laparoscope slideway.

servo control system have to convert the set value. The convert of the set value is necessary to the proper control of the motors shafts velocity and to achieve the set value at the right time. In the algorithm of motor shafts' velocity are minimal and maximal restrictions because of the minimal and maximal motors shafts velocity. The motor shaft velocity are defined by equation:

$$\omega_1 = \omega_t - V_t \frac{\mathrm{ctg}\alpha}{r_t} \tag{10}$$

$$\omega_1 = \omega_t + V_t \frac{\mathrm{ctg}\alpha}{r_t} \tag{11}$$

The controllers with the PID setting are responsible for the motors shafts velocity control. The controllers settings are selected in a way not permitting any slips between friction wheels and laparoscope slideway. The PID gains are experimentally determine by means of the appropriate software provided by the manufacturer of the drivers and motors, which are used in servo drive. Subsequently, the drive mechanism moves the laparoscope slideway. The laparoscope slideway movement is detected by two measuring systems (descriptions of the measuring systems can be found in the next paragraph of this paper). Each of this measuring systems requires an appropriate signal processing because of the necessary data fusion. In the process of data fusion the algorithm combines the advantages of each of the measuring systems, so that this measurement is obtained with high resolution, repeatability and accuracy.

The slip estimator is an important module because of the safety of friction force transmission. The slip estimator determines the friction contact nonlinearity's, by the angle drift of the friction wheels.

The angle drift coefficient is determined by the theory of the road wheel [13] and gives:

$$\delta_{\omega w1} = \frac{F_{\omega w1}}{k_{\omega w1}} \tag{12}$$

$$\delta_{\omega w2} = \frac{F_{\omega w2}}{k_{\omega w2}} \tag{13}$$

Where the forces are as fallows:

$$F_{\omega w1} = \frac{M_1}{r_{t\,\sin\alpha}} \tag{14}$$

$$F_{\omega w2} = \frac{M_2}{r_{t\,\sin\alpha}} \tag{15}$$

Where:

$\delta_{\omega w1}$, $\delta_{\omega w2}$ - the angle drift coefficient in the friction wheels respectively in module 1 and 2,

$F_{\omega w1}$, $F_{\omega w2}$ - the axial force of the friction wheels respectively in module 1 and 2.

The state observes concerns detecting the slip. The algorithm responsible for this task is based on the fuzzy logic systems. This algorithm must be derived outside of the ACS, because of the patient's health. The response of the ACS when the slip will be detected can't be based only on the quantity regulation, as it is important to know the

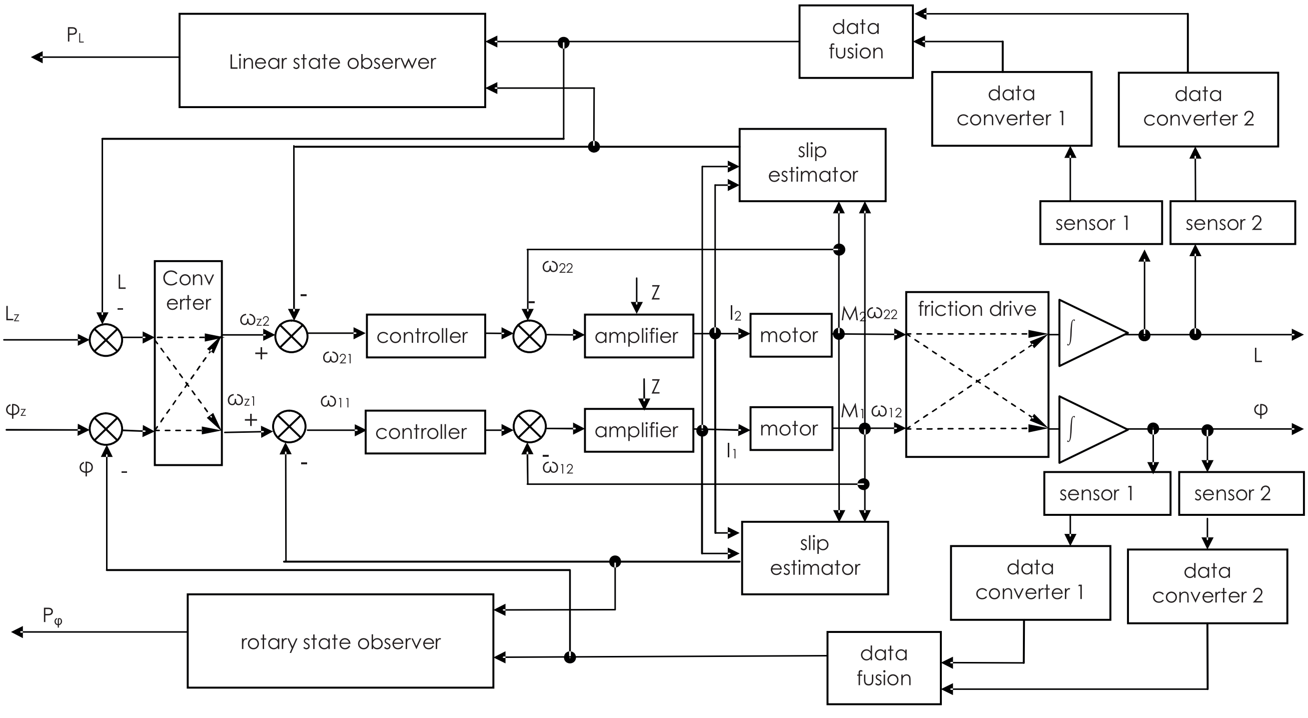

Fig. 3. The block diagram.

L, φ - displacement of the laparoscope slideway respectively linear and rotation. L_z, φ_z - input quantity respectively, linear and rotation. L_r, φ_r - feedback quantity respectively, linear and rotation. ω_{z1}, ω_{z2} - input quantity of the motor shaft respectively 1 and 2. ω_{11}, ω_{12} - rotary speed error of the motor shaft respectively 1 and 2. ω_{12}, ω_{22} - rotary speed of the motor shaft respectively 1 and 2. I_1, I_2, M_1, M_2 - current and torque of the motor respectively 1 and 2. P_i, P_φ - slip quantity respectively, linear and rotation.

cause of the slip and response to it adequately. This involves the change of the input quantity and appropriate reaction of the surgery robot. Obviously, the surgery robot control system can modify the input quantity and the parameters of the PID regulator of the servo drive. The reasons of the slippage may be different. The detection of these reasons will based on the different variables too. The algorithm, which is responsible for detecting the slip reasons will based on:

- angle drift coefficient,
- measurement of the motor current,
- measurement of the motor shaft velocity,
- measurement of the laparoscope slideway displacement,
- force measurement on the laparoscope tool,
- measurement of the robot master displacement,

Depending on this values of measurement, it is possible to detect slippage, and recognize the reasons of the uprising. The most important task of the slippage algorithm is to check up whether that slips occur. This task is realized by the velocity of the motors shafts measurements with angle drift coefficient correction are equal to the laparoscope slideway velocity. If they are equal then the servo drive will work correctly. On the other hand, if it is larger than limit values, it will mean with slippage. The equation responsible for this algorithm is as fallows:

$$P_{min} < \omega_1(1+\delta_{\omega w1}) - \frac{d_{\varphi z}}{d_t} - \frac{dL_z}{d_t}\frac{r_w}{r_t} * \tan\alpha < P_{max} \qquad (16)$$

Where: P_{min} and P_{max} the limit slip estimation value.

The next step is to identify what was the cause of the slippage. If the slip is caused by the change of the friction coefficient through the body fluids that get in to the drive mechanism, it is sufficient to compare the change of the motor shaft velocity value with laparoscope slideway velocity value and check the motor current value. At the time of the slip the motor shaft velocity value increases and the motor current value decreases. An important element in determining of this kind of slip is to check if the slippage is on both modules, because this kind of slip usually appears only on the one of modules (nearest of the patients body). If the slip is only on the one module than surely we have to deal with the slip with the change of the friction coefficient. The ACS reaction to this slip is the change of the input value to gain back the control of the laparoscope slideway displacement. The next move is imposition of the limitation on the motor current value because of the friction force limitation with new friction coefficient. The further strategy is up to the surgeons, who can work with slower servo drive mechanism or stop working for the time needed to replace the drive mechanism.

Another cause of the slip is the high resistant force on the laparoscope slideway. The control system tries to truck with input value and put up the motor current which will result in high force on the friction wheels and braking the friction contact. To identify this kind of slip is measure the laparoscope tool forces. If the laparoscope tool forces decrease when the slippage is detected and the laparoscope slideway does not move, it means that the slip is caused by high resistant force on the laparoscope slideway, for instance from collision of arms. Then the motor current should decrease until there is no slip. After solving of this situation, the servo drive can work without the motor current modification. The recognition of the specific causes of slips and other emergency situations is a very complex process. In addition, the properly chosen strategies for the surgery robot's reaction on the identified emergencies complicate the control of the surgery robot and servo drive mechanism. However, the welldesigned control system greatly enhances the safety of using of the surgery robot.

4. The sensory system

A very important issue concerning the servo drive addition to the drive mechanism and the control system is the selection of the sensors. Recently in the market there are number of sensors with high accuracy, but most of them are useless in the designed servo drive, because of the immobilization these sensors in one of the moving directions of the servo drive. Therefore, it is necessary to create a new measuring system.

A significant limitation, in addition to the requirements of the drive mechanism kinematics, is the need to measure displacement without contact with laparoscope slideway. If there is a contact between measurement element and laparoscope slideway, the measurement element must be sterile because the servo drive is designed for the surgery robot.

4.1. Triangulation laser

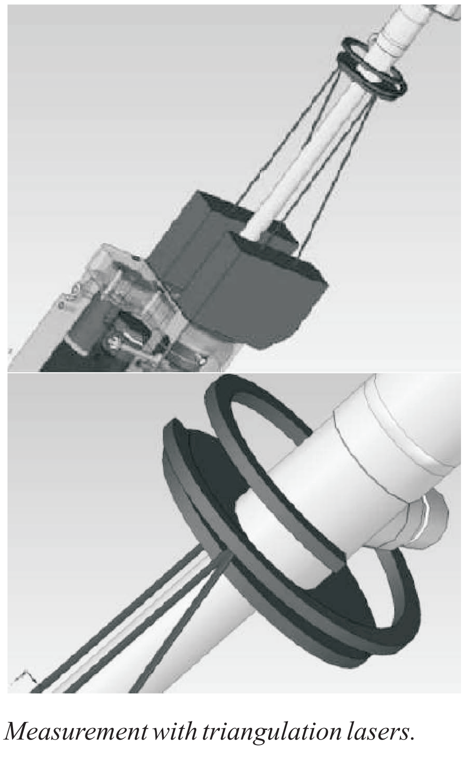

Fig. 4. Measurement with triangulation lasers.

One of the solutions is the use of the triangulation laser. At it is known, the triangulation laser measures the distance from the object, but if we use two lasers and one of the lasers will measure distance to the spiral surface and the second will measure distance to the plane surface we can measure both of the movement directions of the drive mechanism (Fig. 4). Then the laser which measures the distance to the plane surface, inform about the linear displacement, the second laser inform about the rotary displacement. The most significant drawback of this method is the point of discontinuity of the spiral, because there is no possibility of measurement. This discontinuity is about 5 degree. This drawback can be limited by the ACS with program restriction, which will prevent the achievement of this point. On the other hand, this restriction will prevent a total rotation and limit the kinematic of the laparoscope slideway. The second problem of this measurement method is the accuracy. The triangulation laser used in the servo drive has 200 mm range with 0,1 mm resolution. The accuracy of this laser is ±0,2 mm. This is less than the minimal requirements of the servo drive which is 0,1 mm.

4.2. The optical sensors used in laser mice

An interesting approach to the measurement of the laparoscope slideway displacement is the use of the laser image processing sensors which are used in laser computer mice. The operation principle of these sensors bases on the comparison of two pictures taken by the CMOS (complementary metal oxide semiconductor) matrix. The controller built into the CMOS microchip tracks movement of all points on the next pictures and transmits this movement information to the computer by the microcontroller. The resolution that can be obtained by this sensors is determined by the DPI (dot per inch) value. For example, if the mouse sensor have 4000 DPI resolution it is equivalent with 0,00635 mm resolution. This resolution is higher than the resolution of triangulation laser sensor.

The problem of using this sensor is the low reliability, and the high sensibility to the changes of the measuring surface. Another problem is the "image flow". There is the "image flow" when the sensor detects a small displacement when it he does not move.

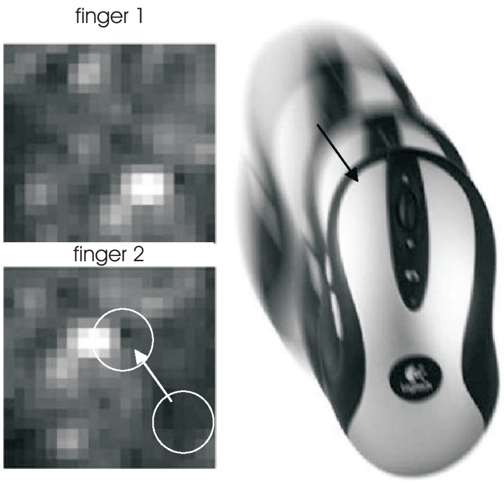

Fig. 5. The operation principle of the mouse sensors [14].

4.3. The summary of the sensory system

If the above described measuring systems work independently they will not be able to provide enough accuracy and reliability of the measuring system. Therefore, they should work together in the servo drive. Then the two measurement systems will support each other and guarantee a sufficient accuracy and reliability of the measurement. In the practice thus system requires an affective algorithm of the data fusion. The results of the data fusion will be presented in the subsequent papers.

5. Construction of the drive mechanism

In the design of the drive mechanism, there were taken the following assumptions.

- the angle between friction wheels and laparoscope slideway are 30 and –30 degree.
- the friction wheels have to be sterile.
- the drive mechanism have to be fast mounted on the Robin Heart surgery robot.
- the drive mechanism have to be small.

The construction of the drive mechanism is shown in the Fig. 7.

The drive mechanism consists of two frames connected by screws. Between these frames there is a pillow, which separates the sterile parts of the drive mechanism. In the non sterile frame there are motors, encoders and elements, which support the stabile connection to the surgery robot Robin Heart.

In the second frame there are two modules with the friction wheels. The modules are mounted to the main frame by the ceramic ball bearings. Both modules can rotate independently. Each of these modules contains a set of the three friction wheels. The friction wheels are between two frames, external and internal, in both of the modules.

The internal frame can rotate and move linearly relatively to the extern frame. This solution of the friction wheels can be pressed to laparoscope slideway. The force to press friction wheels to the laparoscope slideway is obtained by the springs (Fig. 6). The springs are tensioned by the regulation screw. Between the screw and the springs there are the thrust bearing and the separator.

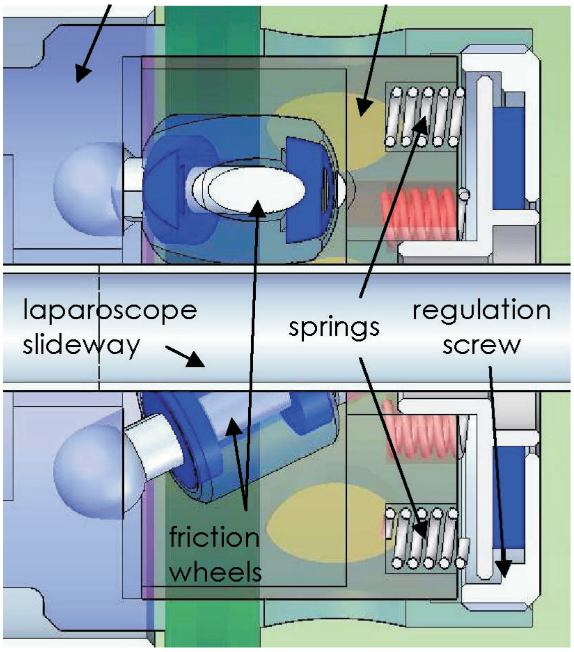

Fig. 6. Construction of the one module.

The friction wheels are composed of the shaft and the sleeve. The sleeve has been mounted by bearings on the shaft. The shaft is spherically ended and can rotate in respect to laparoscope slideway. With this solution we can control the pressing force of the friction wheels to the laparoscope slideway.

6. The summary

The two DOF servo drive with friction wheels has been designed despite of many problems. The servo drive will be used in the surgery robot Robin Heart and will replace the linear drive of the laparoscope camera, or the automatic laparoscope tool. The designed servo drive is smaller than the linear drive that is currently in use. The comparison of the two structures is shown on the fig. 8. The current research in the sensory system will determine the accuracy and reliability of the measurement of the displacement of the laparoscope slideway. One of the important aspects of the control system is the control of the influence of the friction contact on the proper work of the drive mechanism. The next problem is the appropriate design of the state observer, which has to control the slip of the friction wheels. The result of this study will be included in the next publications.

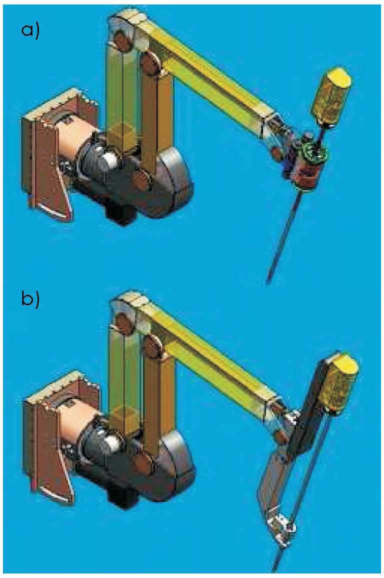

Fig. 8. Comparison of the linear drive: a) designed servo drive, b) the recently used linear drive.

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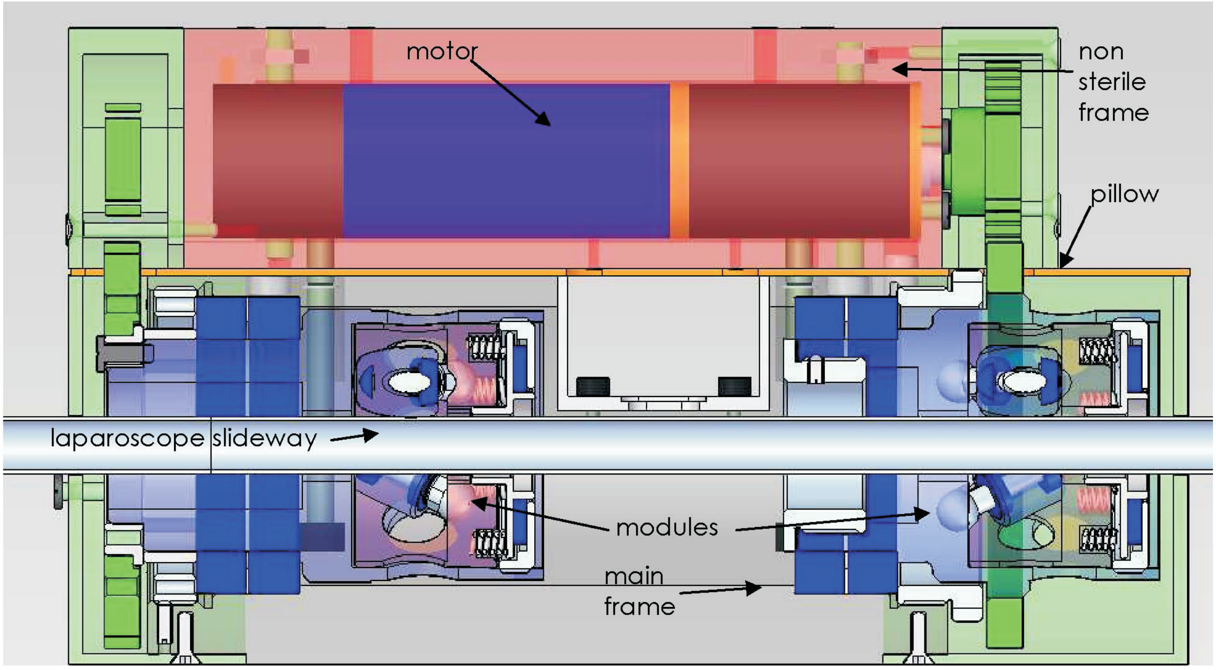

Fig. 7. The drive mechanism construction.

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