Mechatronic modeling of telemanipulator system for minimally invasive surgery

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Abstract: This work proposes a mechatronic model of surgical robot which allows the analysis of relations and flows (of the mass, energy and information) between components as well as specification of their hierarchy in the system. The processing of information and its transmission in the system basis in regard to mechatronic surgical telemanipulator will be also discussed.

Keywords: mechatronic modeling, telemanipulator, robot surgery, minimally invasive surgery, transmission of information

1. Introduction

The idea of use of telemanipulators as the surgeons' helpers in the operating rooms became real at the turn of the 70's and 80's of the twentieth century. Thanks to the development of new technologies, in particular information technology and related to it microchip technology, nanotechnology and modern materials engineering, visual systems and programmable control systems and data transmission, the first trans-continental surgical operation using a robot was performed in the 90's of the twentieth century.

Now, surgical robots allow synergy in a surgeon-patient relations which is primarily reflected in shorter post-surgical recovering period, which directly translates into lower costs of treatment of the patient. In addition, smaller post-operative cuts and smaller blood loss are becoming the main factors that are associated with the significant reduction of complications caused by infections in post-operative statistics resulting in difficult healing cuts. Consequently, the surgeries executed in that way contribute to better post-operative cosmetic effect on the patient's body. As far as the support of a surgeon is concerned, the use of the surgical robots or other mechatronic manipulators in surgical practice significantly improves the precision of the work being done. This is due to providing greater stability of the tools' movements (the movement scalability), by eliminating the negative fatigue factors, e.g. surgeon's involuntary hand trembling.

A large part of the currently designed in the world solutions dedicated to minimally invasive surgery (MIS) is in the phase of laboratory tests. In fact, there are only a few commercial products available on the market that are unequivocally associated with surgical telemanipulators.

In connection with the initiated work at the Faculty of Mechanical Engineering of Bialystok University of Technology on the development of the construction of surgical telemanipulator's arm, a mechatronic model of the surgical robot will be proposed in the further part of this work and a mechatronic approach to the transmission of information in such a system will be discussed.

2. Mechatronic model of surgical robot system

By analyzing advanced structures, e.g. "Da Vinci" surgical robot [7] and the "Zeus" surgical robot [8] and Polish cardio-surgical robot "RobInHeart" [9], in terms of their operational abilities and sophisticated design solutions as well as in terms of the way the control and human-machine interface is used, it can be concluded that in order to build a surgical robot for laparoscopic procedures, it is necessary to consult the concept within the team of experts, specialists from many disciplines. It is important to develop a common interdisciplinary level of agreement between engineers participating in the design process, which can be provided by well-educated mechatronics engineers. They will ensure the appropriate integration of the mechanical, electronic and software components, thus the synergy in the system will be achieved.

To determine the needs of the entire surgical robot's system used for MIS, the approach proposed by Gawrysiak [1] for the analysis of the system of the car brake and further used by the author of this work in his doctoral thesis [6] to describe the positioning of the beam of the pulsed laser can be applied. In the construction of the model, which unites the most important aspects related to the design of the mechatronic system, one can use the model that defines the mechatronic action system shown in fig. 1.

In this general model, three subsystems can be distinguished amongst which the proper movement of mass, energy and information can be assigned. Therefore, the human subsystem of goal settings intercepts and issues information (data, commands) for the electronic information subsystem. Electronic information subsystem accepts such information, processes it, and also has to generate communication with other systems. Whereas, the mechanical actuator system has the attributes of mass and energy assigned, and that is why such energy must be supplied to the system and processed.

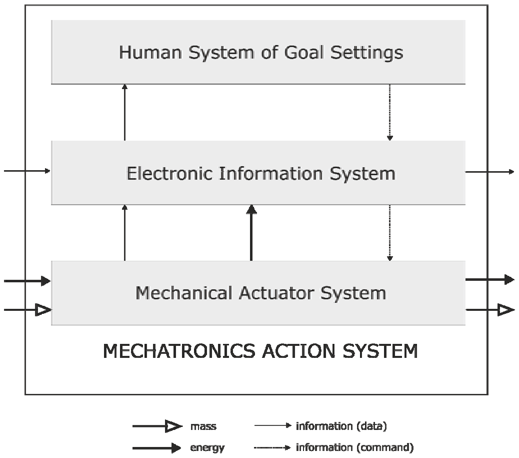

Fig. 1. General structure of mechatronic action system

Rys. 1. Ogólna struktura mechatronicznego systemu działaniowego

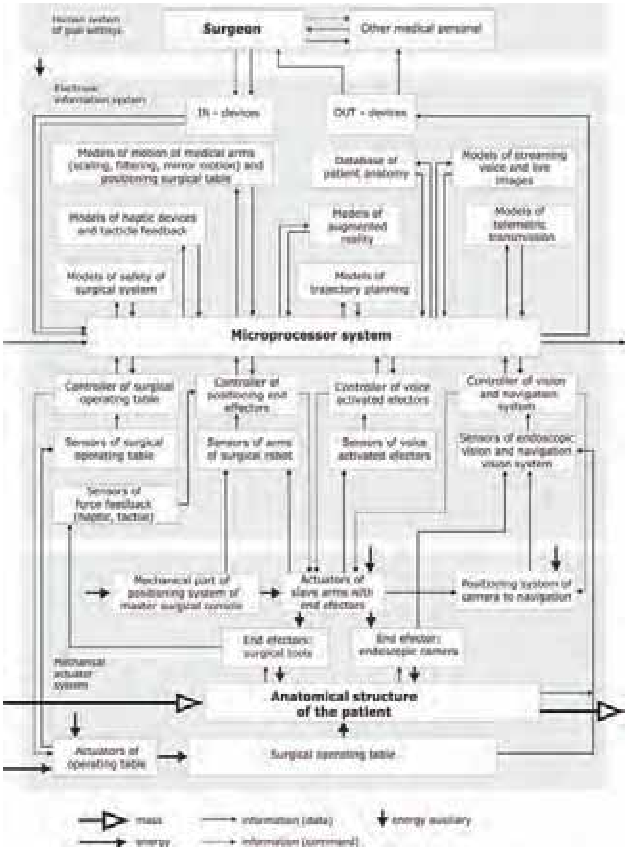

Fig. 2. Mechatronic model of surgical telemanipulator system for minimally invasive surgery

Rys. 2. Mechatroniczny model systemu telemanipulatora chirurgicznego dla operacji małoinwazyjnych

In order to describe the connections made between the components, and to be able to track the relations among the subsystems of the surgical robot with regard to its function, adopted structure and hierarchy (assuming different synthesis possibilities), a mechatronic model has been created (fig. 2) [5].

Certain simplifications were deliberately used in this model which exclude, e.g. power supply systems for each component, so that the diagram becomes more readable. Specialized diagnostic devices or other typical operating room equipment were not included in this model as well. This model contains the most significant components from the point of view of the newly designed system and may serve as a kind of guide for surgical robots designers.

In the designed model the human system of goal setting (the subsystem) is constructed of the two main blocks: 1) the block associated with the surgeon performing the operation and 2) the block representing the remaining medical personnel in the operating room. The surgeon issues all the commands for the input devices, reads the information appearing on the screens and displays of endoscopic cameras as well as from an external navigation system. At the same time he communicates with the remaining medical personnel in order to, e.g. determine the current readings of the patient's vital functions by giving the appropriate commands. The information about the current progress of the operation simultaneously goes from the output devices to the assisting medical personnel.

Central component of the robot's mechatronic system is the microprocessor subsystem. It is located in the electronic information subsystem. Its task is to process information (in the form of data and commands) from the input devices, develop information for the output devices, process the orders for the controllers and read data from the sensory systems. It also processes mathematical models implemented in the control software, which determine algorithms of subsystems operation, and is also responsible for communication with other subsystems.

The subsystem's blocks which define models connected with the movement of the surgical manipulator's arm, calibration of this movement, filtering interference originating from the human fatigue factor (e.g., trembling hands as the result of fatigue in a long-running operation) as well as relating to the determination of the optimal position of the surgical table by taking into account the established safety criteria and models of force and tactile feedback, belong to the software components that control the robot. This software, as in majority of available commercial solutions on the market, should ensure, besides the control of actions in the course of the operation, the pre-operational procedures as well. Those steps can include the planning of appropriate movements in order to carry out the surgeon's given task. In order to be able to do it in practice, database of anatomical structure of the human is being used while planning the path of the movement of each arm of the surgical manipulator. When processing the information about the actual objects (human organs) several scenarios can be practiced, using the augmented reality for this purpose. For those reasons, it becomes significant to consider the aforementioned blocks in the control software. In addition, the system controlling the work of the surgical robot, in Master-Slave configuration, must have implemented algorithms of telemetric transmission of information (data and commands) in its software to ensure the proper cooperation of telemanipulator's components. The information that appears on the input/output devices must be appropriately processed by the microprocessor system.

In the case of robots with multiple arms (in laparoscopic surgeries usually two arms are used for conducting of operational activities, the third is used to hold the endoscopic camera) switching between the active arm or a tool is normally executed by the voice commands (apart from the standard switches, e.g. in the form of pedals). Thus, it becomes necessary to provide parallel visual feedback (e.g. stereo-visual system), so that the surgeon can see the surgical field.

The microprocessor system also supports the controllers responsible for the appropriate setting of the operating table. The controllers provide service to the robot's end-effectors, support for the voice commands and processing of the current image of the operational field. The information about individual components' status is obtained from the appropriate, assigned sensory system.

In the presented model of the executive mechanical system blocks are included which symbolize actuators responsible for, i.a. positioning of the end-effectors of the robot's arms (endoscopic camera and other surgical tools), for the positioning of the operating table and an external navigation system. In order to work, each of these components requires energy. It may be in the form of energy resulting from the movements of the motion system of units in Master operating console and also the form of the energy supplied from the power system (fig. 2). The end-effectors also have an energy impact on the patient's body (endoscope, working tips of the surgical tools), simultaneously sending information to force feedback subsystems.

The mass flow in the proposed mechatronic model refers to the block related to the patient himself. The patient along with operational unit of the surgical robot form a working pair. The support and maneuvering for the given system is provided by the operating table which in its ability to change orientation in relation to the surgeon and the surgical robot's arms extends the capabilities of positioning.

3. Transmission and information processing in mechatronic system

In any system, besides of the flow of mass and energy, one can also distinguish the flow of information. Therefore, an important element of any mechatronic system is the information itself and a method of its processing. The information allows creating relations between subsystems. In case of the system, information may be in the form of data which are read by the sensory subsystem and then processed (transformed) by the microprocessor subsystem. It may also take the form of commands which are introduced to the entry subsystems (used by objectives system, i.e. by a man), and can also be used to give new information, developed on the basis of a command generated by the intentional or associational procedures of the subsystems. The transmission of information "*is the basis for simulation of intelligence, that is accompanied by the extension of the system's wisdom*" [2].

On the basis of the results of his studies ([1–3]) the author has created his own chart (fig. 3) [4], which illustrates the information flow between the levels of the mechatronic system connected with the controlled technical process. In this perspective, the transmission of information occurs locally between the supervision, regulation and control levels of the mechatronic device. This usually takes place in real time, hence it is necessary that processes such as regulation, control in accordance with the established algorithm, or the reading of parameters (their measurement) and estimating the alarm states happen quickly and the system promptly responds to the existing situations.

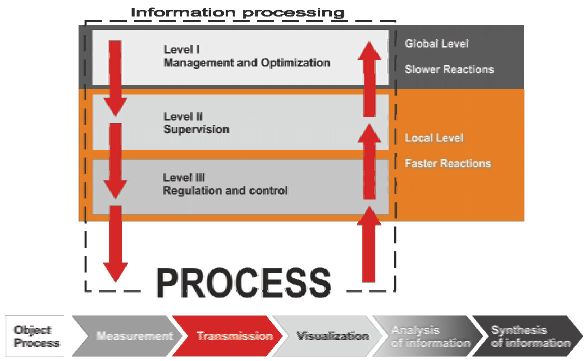

Fig. 3. Levels of information processing in mechatronic system

Rys. 3. Płaszczyzny przetwarzania informacji w systemie mechatronicznym

Physically one can specify these two levels as a system consisting of a mechatronic object (process) (e.g. surgical telemanipulator) and telemetric device of measurement and control. All these data are simultaneously transmitted to the global level connected with coordination of the given mechatronic object (process), where on the basis of the visualized data occurs preliminary analysis of the information and its optimization by the simple monitoring systems, or by the system's operator himself (a human-surgeon). Information created in such way enables management of the device, or the process (for transmission to the lower levels). Unlike local levels these ones have slower reactions and can take physical form, e.g. telemetric client software, installed on the operator's stand.

Therefore, looking at the flow (transmission) of information in a single mechatronic system one can notice that it may have a local nature, for the flow of information in the form of data and commands between particular subsystems (fig. 4) [4].

In this way the essential element of such transmission is the information processing performed by the electronic information system. Depending on the speed of processing of large amounts of measurement and adjustment data by the microprocessor system, on the degree of optimizing control algorithms as well as efficient, high bandwidth communication bus and stable power supply, the impact of the system will depend (regulatory energy processing according to the specified objectives) on the given process. If we take into consideration the transmission of information in case of cooperating mechatronic systems, it can be assumed that it has a global character and has a reference to the impact on the controlled technical process, through e.g. calculation, conversion, management, switching, control, etc., using the established communication channels. Thanks to such solution the systems can cooperate with each other by exchanging necessary information in order to work properly. These channels, in current systems of surgical telemanipulators, usually take form of wireless communication and wired one of a very high data bandwidth.

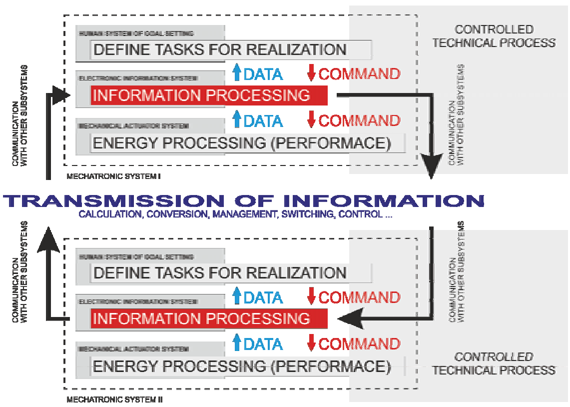

Fig. 4. Transmission of information between the mechatronic system and subsystem

Rys. 4. Transmisja informacji pomiędzy systemami i podsystemami mechatronicznymi

4. Conclusion

The proposed mechatronic model permits an initial analysis of the issues and can be used to define the basic requirements in relation to the proposed biomechatronic system. At the same time, it enables to track the existing relations and to determine the necessary flows of mass, energy and information between components. The general form of the model can contribute to various levels of the system's synthesis.

An important factor for proper functioning and cooperation of the mechatronic device subsystems is a proper information transfer. Without it, in principle, the concept of surgical telemanipulator could not exist. Hence, for the understanding of the essence of the telemetric transmission, its ideas are presented in this work.

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Mechatroniczne modelowanie systemu telemanipulatora chirurgicznego dedykowanego do operacji małoinwazyjnych

Streszczenie: W pracy zaproponowano model mechatroniczny robota chirurgicznego pozwalający na analizę relacji i przepływów (masy, energii i informacji) pomiędzy komponentami oraz określający ich hierarchię w systemie. Omówiono również przetwarzanie informacji oraz jej transmisję w ujęciu systemowym w odniesieniu do mechatronicznego telemanipulatora chirurgicznego.

Słowa kluczowe: modelowanie mechatroniczne, telemanipulator, chirurgia robotyczna, chirurgia małoinwazyjna, transmisja informacji

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