Mechanisms and Machine Science

Amandyk Tuleshov
Assylbek Jomartov
Marco Ceccarelli *Editors*

Advances in Asian Mechanism and Machine Science

Proceedings of IFToMM Asian MMS 2024

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Mechanisms and Machine Science 167

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Amandyk Tuleshov · Assylbek Jomartov ·
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Editors
Amandyk Tuleshov
Laboratory of Intelligent Robotics Systems
Joldasbekov Institute of Mechanics
and Engineering
Almaty, Kazakhstan

Assylbek Jomartov
Laboratory of Experimental Research
in Mechanics
Joldasbekov Institute of Mechanics
and Engineering
Almaty, Kazakhstan

Marco Ceccarelli
Department of Industrial Engineering
University of Rome Tor Vergata
Rome, Italy

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Preface

The first conference on Asian Mechanism and Machine Science, in short Asian MMS, started in Taipei in 2010 as an initiative of IFToMM, the International Federation for the Promotion of Mechanism and Machine Science (MMS), as a specific forum for Asiatic communities to promote better relations and disseminations of MMS activities in Asia. Then, following events were held successfully in Tokyo in 2012, in Tianjin in 2014, in Guangzhou in 2016, in Bengaluru in 2018, and in Hanoi in 2021 in mixed teleconference and presential modes because of the COVID-19 pandemic. This year, the Asian MMS is organized in Kazakhstan by a very active IFToMM member organization. Once again, the conference has attracted a large number of researchers coming mainly but not only from Asia in a wide range of topics, within the spirit of collaboration of the IFToMM mission. This seventh event of Asian MMS is organized in Almaty during 28–30 August 2024 with a program for paper presentations thanks to the great effort of local organizers from U. Joldasbekov Institute of Mechanics and Engineering. The Asian MMS, although primarily intended for Asian countries, serves as a global platform for participants to exchange ideas and present their research work in the several fields of MMS in order to exchange and share new and innovative ideas. The papers in this proceedings volume were accepted after a peer review process and then they are presented in sessions of the conference which covers different topics on History and Education in MMS, Mechanism Design and Theory, Computational Methods, Machine and Robot Design, Gearing and Transmissions, Actuators and Sensors, Dynamics and Control of Multibody Systems, Vibration Techniques, Reliability, Biomechanics, Micro and Nano Systems, Experimental Methods in Mechanics, and Space Engineering and Technology . We have received 78 papers, of which 58 full papers were accepted after the review for presenting and being included in this proceedings volume together with four keynote contributions. The majority of the papers are from Kazakhstan, but submissions came also from other IFToMM communities such as China-Beijing, China-Taipei, India, Japan, Russia, Turkey, and even with collaboration from non-Asiatic countries. We express our grateful thanks to the members of International Scientific Committee for Asian MMS, for the support and promoting activities, namely Marco Ceccarelli (Italy) (Chair), Gondi Kondaiah Ananthasuresh (India), Yusuke Sugahara (Japan), Weizhong Guo (China-Beijing), Yu-Hsun Chen (China-Taipei), Khang Nguyen Van (Vietnam), Erkin Gezgin (Turkey), Jomartov Assylbek (Kazakhstan). We would like to express our sincere gratitude to the reviewers, who contributed to the review process with their experience and expertise in due time with a speedy but rigorous review process. The authors of the papers are also acknowledged for having finalized the papers submission after careful revision according to the review comments. We believe that the published papers can be of interest and stimulus for readers for their future activity also with the aim to contribute with their results to the next events of the Asian MMS. We would like to thank all the team members of the organizing committee at the U. Joldasbekov Institute of Mechanics and Engineering in Almaty, who helped with the conference organization and preparation of these proceedings. We would like to send our also appreciation to the Springer-Nature team for their support and patience in publishing this book in time for Asian MMS conference.

Amandyk Tuleshov
Marco Ceccarelli

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Contents

A Study of Feasibility for a Testbed for Biomechanics Testing of Surgery Rib Retraction

Marco Ceccarelli(✉) and Asif Hasan

University of Rome Tor Vergata, 00133 Rome, Italy
marco.ceccarelli@uniroma2.it, asif.hasan@students.uniroma2.eu

Abstract. A testbed design is presented with a functionality for a lab experimental analysis of biomechanics of surgery in rib retraction with pork rib specimen. The testbed is validated with experiments using a mechanical surgery retractor that is sensored with properly arranged sensor units linked to testbed functionality. Results are discussed to show the feasibility of the testbed and the test significance.

Keywords: Biomechanical Testbed · Thorax · Surgery · Retractor · Sensor

1 Introduction

The biomechanical analysis of the human rib cage is generally carried out using models and dummies in order to determine the response of the rib cage based mainly on the mechanical characteristics of the bone structure of the ribs [1].

There are only a few systems in use that when adapted can experimentally determine the dynamic response of the ribs during breathing or in impact situations. The CN 104180962A patent presents an experimental system for impact tests on mechanical products that can also be used in rib biomechanics applications. The system consists of a hammer on linear guides also used to measure the movement of the hammer and the impact on the specimen. The authors of [2] presents a sensorization with force sensors for two types of sternal retractors (straight and curved ones) with which they got retraction action by the valves in patients during thoracotomy operations. The paper [3], from previous experiences at LARM2 in Rome, presents a testbed for testing artificial ribs in impact conditions with a modular structure whose interchangeability allows impact tests to be carried out with different conditions, including simulation of breathing acts. The impact system is based on a cam mechanism with a cam profile capable of generating the motion in terms of impact time and intensity values on the artificial rib specimen with the possibility of adjusting the impact test in configurations very limited testing. Those existing solutions for biomechanical testbeds that are specifically designed for thorax surgery or trauma evaluation, are used to assess the biomechanics of the chest region, including the rib cage, sternum, and surrounding tissues, to improve surgical techniques, evaluate medical devices, and to understand thoracic injuries.

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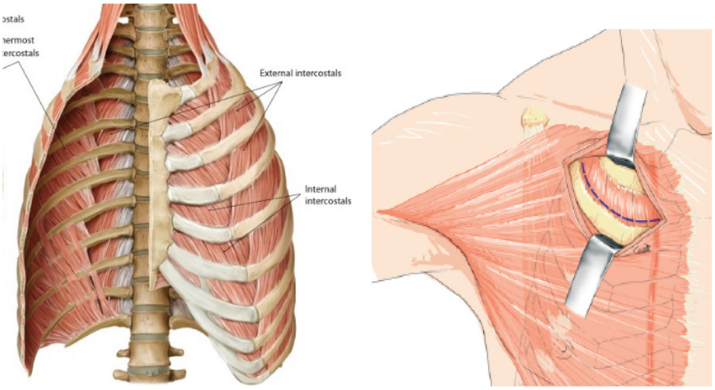
The main objective of the reported work is to design a sensored testbed for biomechanics evaluation of surgery actions on the thorax. Main functionality is planned to simulate and measure mechanical behavior of the chest under various conditions. The designed testbed can also be used for analyzing the response of a thorax in different invasive surgeries and for evaluating impact, compression, or other forces, whose analysis is crucial for understanding thoracic injuries and developing safety measures.

2 Requirements

The ribcage provides structural support to the thoracic cavity, protects internal organs, and assists in the breathing process by allowing expansion and contraction during inhalation and exhalation [4–7]. There are 12 pairs of ribs in human thorax, Fig. 1 a). They are categorized into true ribs (1–7), false ribs (8–10), and floating ribs (11–12). True ribs (1–7) are directly attached to the sternum via costal cartilage. False ribs (8–10) are indirectly attached to the sternum through shared cartilage or not attached at all. Floating ribs (11–12) are not connected to the sternum and are only attached to the thoracic vertebrae. Costal cartilages are flexible hyaline cartilages that connect the anterior ends of true ribs to the sternum. They allow for some movement and flexibility in the ribcage during breathing. The sternum is a flat bone located in the center of the anterior thoracic wall. The thoracic vertebrae are the 12 vertebral bones in upper and middle back region. Each thoracic vertebra articulates with a pair of ribs, forming the costovertebral joints.

The surgery rib divarication is shown in Fig. 1 b) as the surgery action by a mechanical retractor to open space between two ribs for accessing the internal thoracic volume. Problems arise in motion and action during such a surgery operation with risks of damage or even breaking of ribs under divarication, later with lot of pain by the patients.



a)

b)

Fig. 1. The attached problem [4–6]: a) anatomy of ribcage; b) a surgery rib divarication.

The main functionality of a mechanical rib retractor can be recognized in the action of providing force necessary to separate the ribs with attention to minimizing the risk of damage and even breaking of the ribs which can induce not only pain problems for the patient but further complications in the surgical operation configuration. Parallel to this force action, the motion that is given to the retractor to provide these force actions, must be considered carefully in its characteristics looking at fundamental requirements for efficiency of the costal divarication. Figure 2 summarizes the aspects which, with their requirements, can contribute to a clear definition of the problems and mainly to an efficient planning of the rib retraction operation with an adequate mechanical retractor in a testbed for evaluation the biomechanics of retraction operation and other operation on the thorax. Referring to rib retraction, the force action must be calibrated to the skeletal resistance capacity of rib bones but also with a configuration that does not produce incisions or even small superficial fractures on the ribs with a progressive negative trend while maintaining an almost constant force action. The movement that is linked to this retractor action, produces the spacing of the two fingers of the rib retractor so to generate a proper gradual movement. Is the action of the surgeon's hand that gives movement to the retractor operating as a mechanical transmission. Therefore, the requirements that can be considered, are related both to the movement of the surgeon's hand with adequate continuity of movement and grip configuration of the actuation retractor element as well as to the produced movement of the retractor finger which acts within the motion configuration of the rib through the surfaces of the retractor valves.

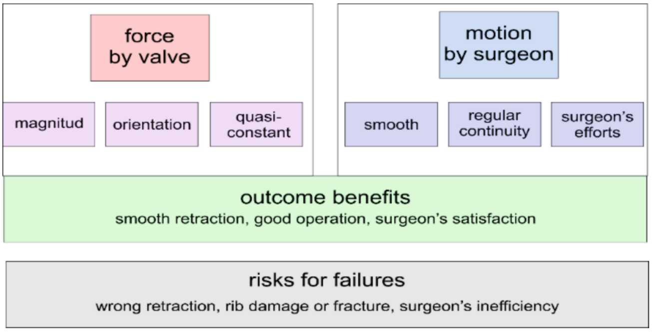


Fig. 2. A scheme for requirements in design and operation of a testbed for biomechanics evaluation of thorax surgery

The values reported in Table 1 are intended to be an example of reference values in consideration of the current mechanical retractors such as Finocchietto type to ensure efficiency of the rib retraction operation, reducing the risk of damage to the ribs, and adequate action by the surgeon to avoid situations of biomechanical stress.

Table 1. Values of reference for requirements in rib retraction evaluation

Rib divarication	Rib incision	Retractor force	Execution time
5.0–10.0 cm	3.0–2.0 cm	10.0–100 N	60.0–300.0 s

3 Conceptual Design

Figure 3 shows a conceptual design of the proposed testbed as a solution that considers the requirements in Fig. 2 and Table 1. The proposed testbed for biomechanical experimentation on rib specimens is composed of a mechanical structure with profiled bars (1) with two gripping clamps (2), a pushing mechanism (3) actuated by a motor (4) with encoder (4b), two force sensors (5) on the clamp and one (5b) on a rib specimen, one deformation sensor (6) and one IMU sensor (7b) on specimen, one IMU sensor (7) on pushing mechanism head, one video tracking sensor (8) with marker for position monitoring with motion capture system (8), a signal acquisition and processing unit (9), a data storage unit (10), a connection interface and data transmission (11), a power supply unit (12). The testbed is aimed to reproduce and to monitor situations of stress and even impact on specimens of artificial ribs and animals that in Fig. 3 are modelled as a unit with a red line that is fixed by the gripping clamps (2). The pushing mechanism (3) is aimed at performing pushing or impulsive forces on grasped rib unit.

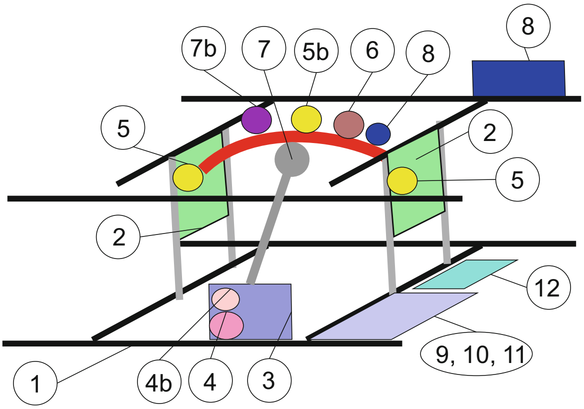


Fig. 3. A scheme of conceptual testbed design with main components [3]

4 Mechanical Design and Its Sensorization

The testbed is built with a modular reticular structure as per the conceptual design in Fig. 3 by combining it with sensor units that are selected properly for being installed on the specimen and on the testbed structure. The reticular structure is designed as reported in the CAD design of Fig. 4a) with rods that are fixed by means of easily removable screw connections to adapt the configuration of the reticular frame to the different experiments. Two gripping systems are also installed as removable and positioned as required by a specific experiment. The reticular structure has a wide base to ensure static stability but also to permit installation of additional rods. Furthermore, the structure is designed to be easily transportable also for convenient and comfortable positioning of an operator when carrying out experiments. Figure 4 b) shows a first solution of the pushing mechanism that is designed for tests including external actions on the specimen to simulate both anatomical conditions and accident situations with more or less impulsive impacts.

The additional two sensor units are designed with sensors for monitoring movement and force with design solutions using market products with structures that can allow easy installation on the test specimen, as shown in Fig. 5.

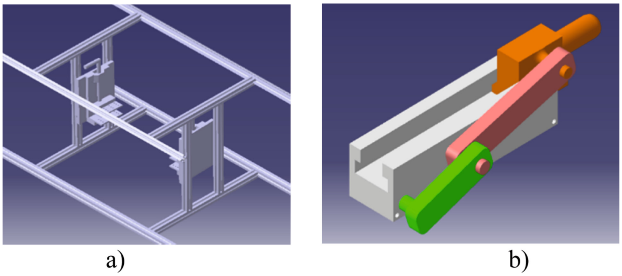

a) b)

Fig. 4. Mechanical design of the proposed testbed in Fig. 3: a) CAD design of the frame; b) CAD design of the pushing mechanism

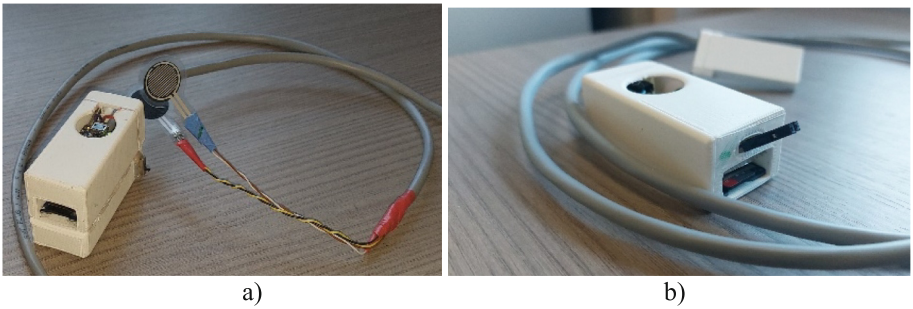

a) b)

Fig. 5. Sensor units with rechargeable battery and onboard data storage: a) Force FSR sensor unit; b) IMU-based motion sensor unit

FSR force sensors are used for measuring retraction force on rib bones on both retractor finger valves. For a proper installation avoiding interference with the action of the surgeon, the sensors are connected with a long cable to a box with nano-Arduino microcontroller and a compact rechargeable battery, making the sensor device ergonomic and easy to use. The used FSR sensors are selected from market products to have a capacity of 500 N with a size of 1.5 cm of diameter to properly fit in the valve surface. The full sensor unit is shown in Fig. 5a).

For measuring the motion of the movable finger of a Finochietto-type retractor a IMU sensor is used. In order to keep the unit compact and efficient, it is integrated in a Nano Arduino Iot-33 that is selected from market products. The IMU has a capacity of 10 g with a size of 1.0 × 3.5 cm to properly fit on the retractor finger upper surface. Similarly to the force sensor unit, it is connected with a long cable to a box with a compact rechargeable battery, making the sensor device ergonomic and easy to use. The full device is shown in Fig. 5b).

The frequency of data acquisition for both sensor units is settled at 104 Hz. The stored data on onboard SD card can be later read and analyzed in a PC.

5 A Prototype and Lab Experiences

A prototype of testbed frame is made by using aluminum alloy extruded bars for easy assembling with screw elements. 3D printed parts are manufactured from CAD designs to make the box and all the structure to contain the electronic of the sensor units. Thus, a layout for lab testing is experienced in the illustrative case of rib retraction as shown in Figs. 6 and 7 with a pork rib sector using a small Finochietto-type mechanical retractor. Different types of retractors can be used in the experiments as per the general structure of the testbed both in clamps configuration and sensor units not fixed on it. The testbed is used to install single ribs or set of rib from a thorax portion so that once a retractor is installed into an incision of the specimen, the retraction operation is performed by an operator while acquiring data from sensor unit on the monitored retractor.

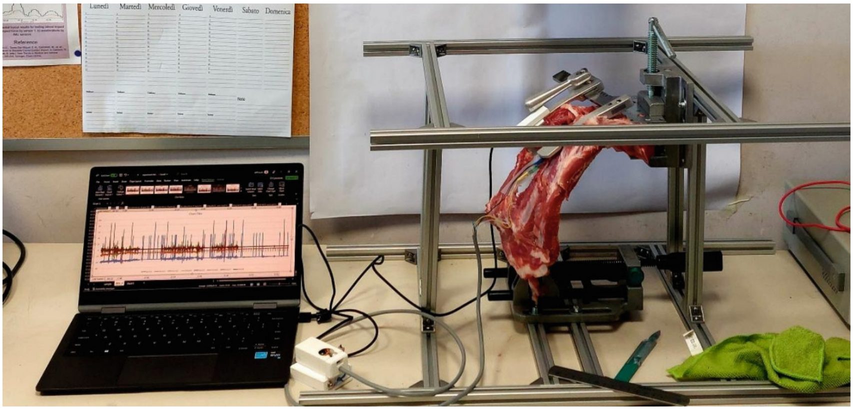


Fig. 6. A lab layout for testing with a Finochietto retractor installed on a rib under test

Experiments were worked out with pork specimen with a lay out set up as in Fig. 6 with the monitoring of the retraction test by using the sensor units in Fig. 5 while performing the retraction up to a final open divarication useful for hand insertion, Fig. 7. A test was repeated three times using two specimen of 800 g with size of 19.0 × 18.0–25.0 cm of ribcage from a male pork of 170 kg. The divarication tests were run with a duration of 50.0 – 80.0 s.

Illustrative results of testing are reported in Fig. 8 as referring to the illustrative example in Fig. 7 in terms of retraction force and motion to show both the feasibility of the design sensored testbed and its efficiency in giving useful results of biomechanics characterization of a retraction simulated operation. Figure 8 displays the acquired force exerted by the valves on the finger of the used mechanical retractor of Finochietto type and the acquired motion of the movable finger that is actuated by the operator hand during two cycles of divarication.

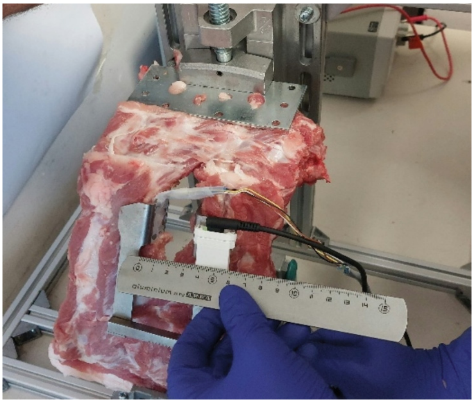
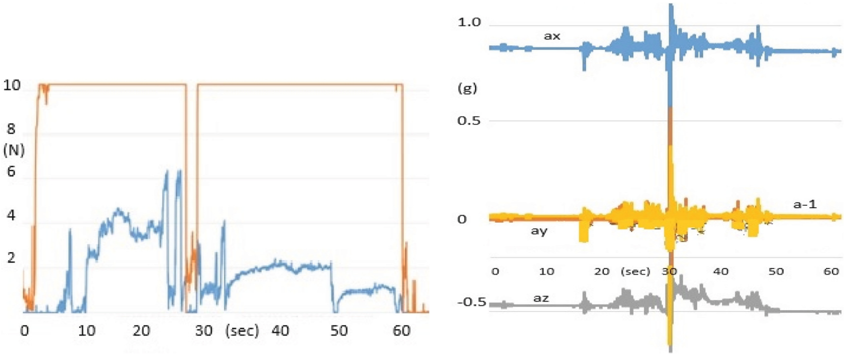


Fig. 7. A test example with pork rib divarication with Finochietto retractor.



a) b)

Fig. 8. Illustrative results from test in Fig. 7: a) acquired valve force: b) acquired acceleration of divaricator finger.

In Fig. 8 a) the acquired force show that one valve was well acting on the rib under retraction even up to saturating the force sensor capacity of 10 N, while the other one shows alternative reaction as due to not constant contact with probably also a not well complete adhesion to the rib surface. Figure 8 b) shows small variations of finger acceleration but in the short time of stopping and restarting the divarication the acceleration is experience with high values indicating very likely final and initial conditions of the divarication with impacts of the valves against the rib surface that make the operator action with impulsive action. The value of X component is sensed with the gravity that is then subtracted in the calculation of acceleration magnitude.

The reported test results give hints on the expected goals from the analyzed requirements for design and operation of biomechanics evaluation of rib retraction in a test bed for better thorax surgery in terms of indicating numerically the significance of the motion regularity and retractor force effects.

6 Conclusions

This paper presents a proposed design for a test bed structure for the experimental analysis of the biomechanics of surgical operations on the thorax using artificial or animal specimens. The structure is designed with a modular structure to have the possibility of rapid reconfiguration depending on the surgical situations and experimental tests that is planned to carry out to analyze the relative biomechanics. Furthermore, the sensorization is designed and therefore developed with the particularity of not being rigidly installed on the testbed structure also to have the possibility of simulating surgical operation situations where such sensorization does not have to create further constraints or impediments to the surgeons' actions. First laboratory experiences are reported with satisfactory results for future development of both the testbed and its use in more specific experimental campaigns such as the one proposed as an example referring to the surgical rib retraction.

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Experimental Research of a Cable-Suspended Parallel Robot with Point-Mass End-Effector

Assylbek Jomartov(✉), Amandyk Tuleshov, Aziz Kamal,
and Azizbek Abduraimov

Joldasbekov Institute of Mechanics and Engineering, 050010 Almaty, Kazakhstan
`legsert@mail.ru`

Abstract. In this work, experimental researches of the Cable-Suspended Parallel Robot (CSPR) with point-mass End-Effector (EE) were carried out to determine the tension in the cables. A device for measuring cable tension, consisting of three pulleys and a force sensor has been developed. A device for measuring cable tension is easily mounted on the frame for various types of CSPR with point-mass EE and connected to the ZET 017 measurement module. Experimental researches were carried out to determine the tension in the cables of a CSPR with point-mass EE, for various trajectories of movement EE. Information about the actual tensions in the cables makes it possible to assess the performance of the CSPR with point-mass EE. For normal operation of the CSPR with point-mass EE, constant monitoring of the tension of its cables is necessary.

Keywords: Cable-Suspended Parallel Robots · End effector · Point-mass · Prototype · Tension · Force sensor · Trajectories

1 Introduction

The cable-driven parallel robot (CDPR) is one kind of parallel robot that is widely used in the world. The rigid links of conventional parallel robots are replaced with flexible links (cables) (see Fig. 1a) and as a result, CDPRs are obtained (see Fig. 1b) [1]. CDPRs are widely used to solve practical complex problems due to their large workspace [1]. CDPR cables can only work in tension, and lose their performance when compressed. The CDPR cables remain functional only under tensile forces and lose their performance when compressed. This feature greatly limits the development and use of CDPRs and requires its consideration when developing new CDPRs.

The CDPR structures have different locations of the cables relative to the EE. A CDPR that has cables located above the EE is called suspended [1–4]. A CDPR that has at least one cable located below the EE is called non-suspended [5–8]. The Cable-Suspended Parallel Robot (CSPR) with point-mass EE is of particular interest [9].

The CSPRs with point-mass EE are a group of suspended CDPR in which all cables are attached to one point on the EE and to simplify the modeling, we assume that its mass is concentrated at a given point. A CSPR with EE point mass, due to its parallel design, has less EE swing and is well suited for loading and unloading operations. Let us further refer to a CSPR with point-mass EE as a CSPR for convenience.

A CSPR with four drive cables is shown in Fig. 2.

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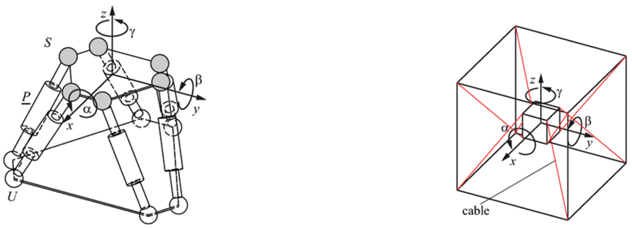


(a) (b)

Fig. 1. Robots of parallel structure: a) Stewart parallel robot; b) CDPR

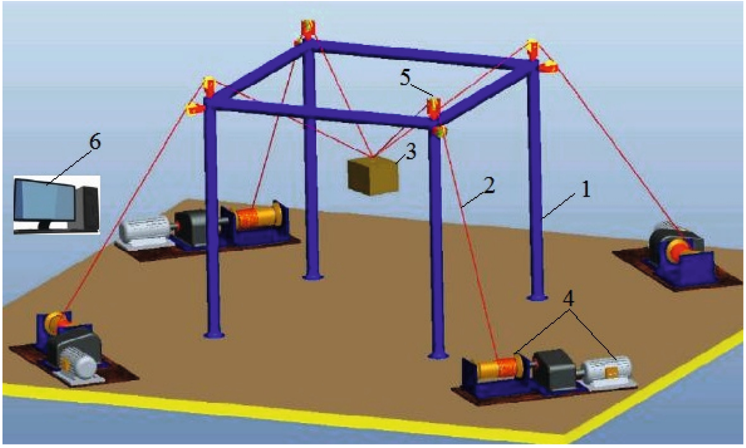


Fig. 2. A CSPR with 3 DOF and four drive cables

All drive cables of the CSPR are located above the EE (see Fig. 2). As can be seen from Fig. 3, the CSPR has a metal frame 1. Servomotors with winches 4 are installed on the base of the frame in the four corners. Cables 2 are connected to EE 3 through pulleys 5, and the other ends of the cables are connected to winches. The position EE 3 is set by winding or coiling the cables 2 onto winches with servo motors 4. Winches with servo motors 4 are controlled through the control unit 6.

A CSPR shown in Fig. 2, EE has three translational DOF. The location of the cables of the CSPR eliminates the interaction of the cables with each other and surrounding objects [10–15]. The load capacity of the CSPR and the workspace are increased in connection with this. The disadvantage of the CSPR is the low vertical rigidity, which can lead to fluctuations of EE in due to the influence of external forces. Fluctuations of EE lead to errors in tracking the trajectory of a CSPR.

The experimental researches of CSPR, in order to determine the tension in the cables, are necessary for their practical use. Information about the actual tensions in the cables will allow one to evaluate the performance of the CSPR. This paper conducts experimental research on the CSPR.

2 Prototype of a CSPR

A prototype of a CSPR was made to conduct experimental researches (see Fig. 3). Frame dimensions are a = 1,485 m, b = 1,230 m, h = 1,565 m and mass EE is m = 1.0 kg. The cables are driven by four winches. Winches are driven by four stepper motors with drivers (see Fig. 3). The stepper motor drivers are connected to the computer via a USB port using a controller. Four tension sensors were used to determine the tension of the cables.

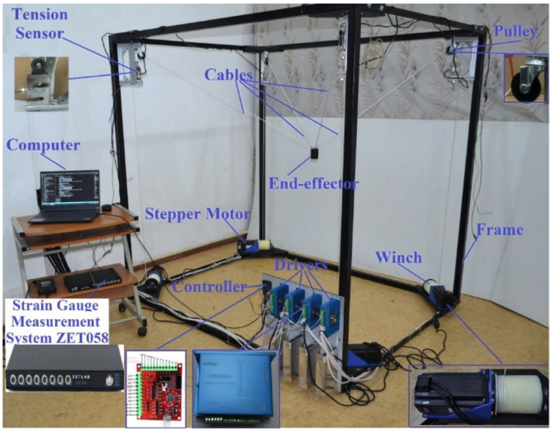
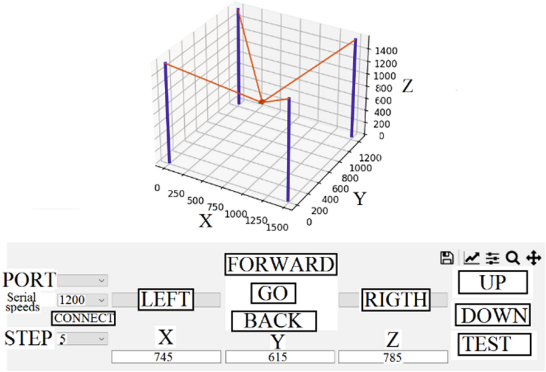


Fig. 3. A prototype of a CSPR

The control interface of the CSPR is shown in Fig. 4.



Serial speeds 1200

STEP 5

X 745

Y 615

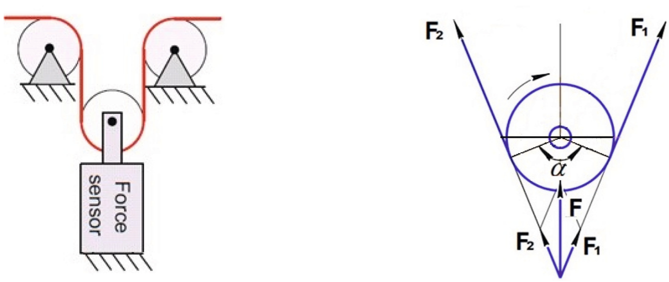
Z 785

Fig. 4. The control interface of the CSPR

We can manually control the EE using the CSPR control interface. You can perform manual EE translation movements (see Fig. 4). It is possible to reproduce its various trajectories specified by curves.

2.1 Device for Measuring Cable Tension

A device for measuring cable tension, consisting of three pulleys and a force sensor (see Fig. 5), was made.



(a) (b)

Fig. 5. A device for measuring cable tension

When determining the resultant force F acting on the force sensor (see Fig. 5a), from the tension of the cables F_1 and F_2, we can assume with a sufficient degree of accuracy that

$$F_1 = F_2,$$

from Fig. 5b we have

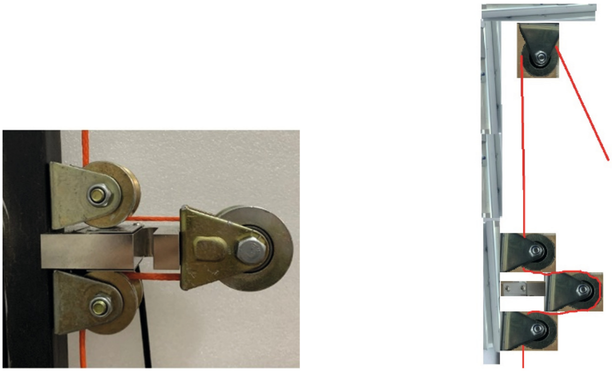
$$F = 2F_1 \cdot \sin\frac{\alpha}{2},$$

where α is the angle of wrap of the pulley by the cable. The angle of wrap of the pulley by the cable (see Fig. 5a) is equal to $\propto = 180^\circ$, then $F = 2F_1$, hence the tensions of the cables are determined by the formula

$$F_1 = F_2 = \frac{1}{2}F$$

The made device for measuring cable tension is shown in Fig. 6a. The device for measuring cable tension is easily mounted on the frame (see Fig. 6b) of various types of CSPR.

The device for measuring cable tension is connected to the ZET 017 measurement module [16], according to the diagram shown in Fig. 7.



a) b)

Fig. 6. a) Side view of the device for measuring cable tension; b) option for installing a device for measuring cable tension on the CSPR frame

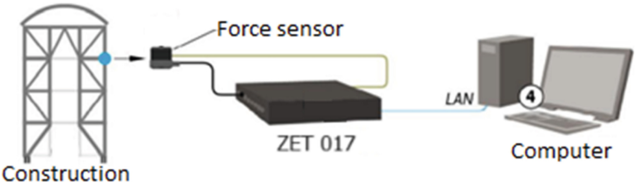


Fig. 7. Connection diagram of the ZET 017 measurement module device for measuring cable tension

3 Experimental Results

Experimental studies to determine the tension in the CSPR cables were carried out. EE with mass of 1 kg moves along a circular path (1) with radius r = 0.25 m.

$$\begin{cases} x = 0.25\cos 0.2\pi t, \\ y = 0.25\sin 0.2\pi t, \\ z = 0.9 \\ 0 \le t \le 10. \end{cases} \tag{1}$$

As a result of experimental studies, cable tension graphs were obtained, which are shown in Fig. 8.

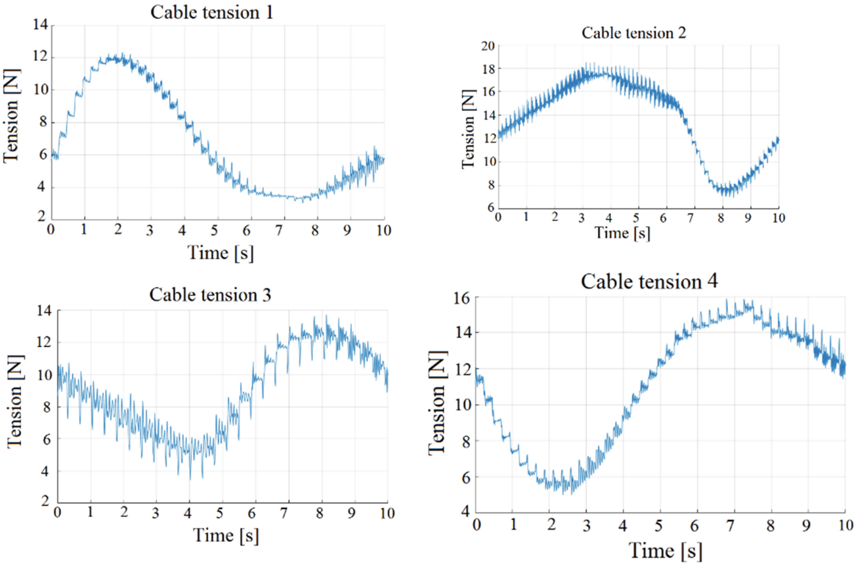


Fig. 8. The graphs of cable tensions

Experimental studies were carried out to determine the tension in CSPR cables, when moving an EE with a mass of 1 kg, along the trajectory shown in Fig. 9. Experimental graphs of cable tension when moving along a rectangular stepped path are shown in Fig. 10.

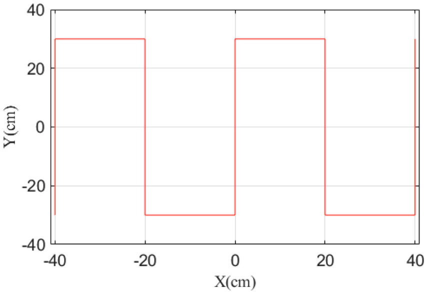
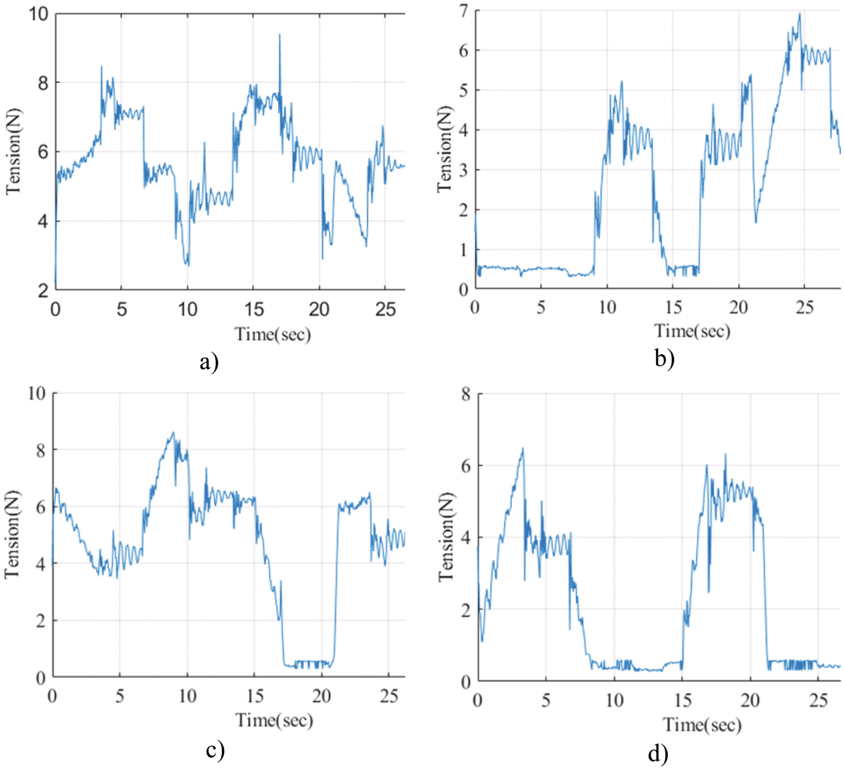


Fig. 9. Graph of the rectangular step trajectory EE of CSPR

As can be seen from the graphs of the tension of the cables of the CSPR with a rectangular stepped trajectory of movement of its EE, that there are large fluctuations and jumps in the tension of the cables, causing swaying of its EE.



a) b) c) d)

Fig. 10. Experimental graphs of cable tension: a) 1-th cable, b) 2-nd cable, c) 3-rd cable, d) 4-th cable

4 Conclusion

In this article, experimental studies of the CSPR to determine the tension in the drive cables were carried out. A prototype of CSPR with a control interface was designed sensor has been developed. The device for measuring cable tension is easily mounted on the frame for various types of CSPR and connected to the ZET 017 measurement module. Experimental studies to determine the tension in the cables of a CSPR, when EE is moving in a circle and along a rectangular stepped trajectory were carried out. From the analysis of the cable tension graphs with a rectangular step trajectory of the EE movement, it is clear that large swings occur. It is necessary to make changes to the CSPR control system to eliminate EE swing. In this regard, constant monitoring of cable tension in the CSPR is necessary for normal operation.

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