Design and Balancing of a Novel 2R1T Manipulator with Remote Center of Motion

Tuğrul Yılmaz [1[0000-0002-3853-8020]] and Gökhan Kiper[1[0000-0001-8793-724X]]

[1] Department of Mechanical Engineering, İzmir Institute of Technology, İzmir, Türkiye
gokhankiper@iyte.edu.tr

Abstract. The paper presents a novel manipulator design to be used as an endoscope holder for endonasal skull base surgeries. The manipulator should provide two rotational and one translational motions for the endoscope, where it should be able to be oriented about and slide along the tip of the nostril of a patient as a pivot point. First, suitable manipulators with remote center motion are investigated. Manipulators with serial and hybrid kinematic structure and redundant manipulators with a passive joint are examined. A serial manipulator with a circular arc as the second rotation axis is chosen for the detailed design. The novelty of the kinematic structure of the manipulator is that the end-effector heave motion is achieved in a tangential direction to the circular arc. The constructional design and counter-mass balancing solution for the manipulator are presented. The total assembly mass is 11.6 kg for navigating an endoscope of 0.44 kg mass.

Keywords: Medical Robotics, Serial Manipulators, Remote Center of Motion.

1 Introduction

Manipulators with remote center of motion (RCM) are utilized where an end-effector needs to move around a pivot point without any physical contact at this point. They are used for minimal invasive surgery [1-4] and manufacturing applications [5]. RCM can be obtained in three different ways: mechanically constrained RCM, RCM by passive joints and programmable RCM [3]. For a programmable RCM, a controller is used together with a redundant manipulator to obtain RCM around a pivot point. Although programmable RCM provides freedom in design, the control is complicated and in case of a security breach, such a manipulator poses danger for the operation. Another way to obtain RCM is locating a passive joint at the pivot point which provides predetermined degree-of-freedom (dof) around it. Using RCM with passive joints provides flexibility in mechanism design, but it is problematic if translational motion is required for the end effector. Mechanically constrained RCM manipulators are obtained by constraining the motion around the pivot point via the kinematic structure of the manipulator. They are safer compared to programmable RCMs and they provide easier movement than RCM obtained by passive joints. In the literature, there are many different types of RCM mechanisms such as circular tracking arc, parallelogram, spherical linkage, parallel manipulators, isocenters, synchronous belt transformation, etc. [2].

This paper presents a manipulator design with RCM for an endoscope holder to be used in endonasal skull base surgeries. This surgery is currently carried out as a minimally invasive surgical (MIS) operation, where the endoscope and all other tools are inserted into the skull through the nostrils. The manipulator is to be oriented and also slid through an approximately fixed point at the nose tip. Due to the motion characteristics, the required motion is two rotations (yaw and pitch) and one translation (heave), i.e. a 2R1T motion. Yaşır et al. [6] presented structural synthesis for 2R1T manipulators with RCM. Then they proposed a 2URRR-URR type parallel manipulator for MIS [4]. Yaşır et al. [7] and Aldanmaz et al. [8] proposed gravity balancing solution for the manipulator presented in [4]. This paper presents a serial manipulator as an alternative solution for the same application. Also a gravity balancing solution is presented.

In endonasal skull base surgery application, the endoscope holding manipulator should be located on the top of the patient's head in order to avoid interference with the surgeon's hands and the surgical tools (Fig. 1). The endoscope goes through a nostril, so its angular motion range is limited. In Fig. 1, gravity is along –y direction and the xy-plane represents the sagittal plane of the patient. Dede et al. [9] determined the target workspace using an absolute gyroscope. The resulting orientational workspace is determined as follows: The endoscope axis makes an angle of 12°-to-45° with the y-axis (pitch angle) and an angle of 1°-to-22° with the xy-plane (yaw angle). Also, using tomography data, the target heave motion range is determined as 100 mm.

The rest of the paper is organized as follows: Section 2 presents alternative serial and hybrid manipulator structures suitable for endonasal skull base surgery application. Section 3 presents the selected manipulator's constructional design. Section 4 presents the counter-mass gravity balancing solution. Section 5 presents conclusions.

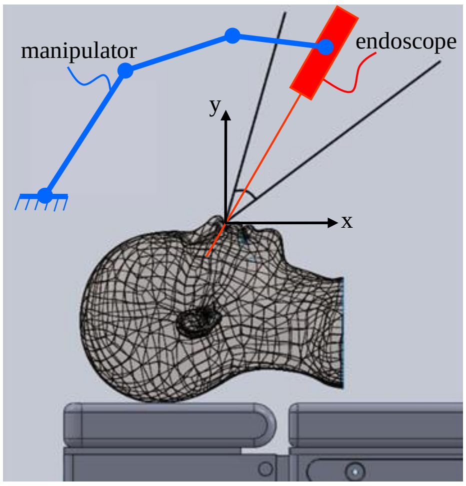

Fig. 1. The positioning of the endoscope holding manipulator.

2 Serial and Hybrid 2R1T Manipulator Structures

Yaşır et al. [6] present several serial, parallel and hybrid kinematic structures for 2R1T manipulators with RCM. The serial manipulator (s-s-s) comprises an RRP (R: revolute, P: prismatic) kinematic chain, whereas three type of hybrid structures are mentioned: type 1 (s-2p): the first R of the 2R1T motion is serially connected to a 2-dof parallel kinematic chain (PKC) for the RT motion; type 2 (2p-s): 2R motion is obtained with a PKC (see [1] and [5] for several alternatives) while the T motion is connected serially; type 3 (s-p-s): second R motion is obtained with a PKC while the first R and the T motion are connected serially. Yaşır et al. [6] mostly focus on PKCs, whereas the focus of this paper is on serial and hybrid kinematic structures with different constructions which could be suitable for endonasal skull base surgery application.

2.1 Serial Structures

Some serial RR manipulator designs with RCM are presented in [5]. Here, two alternative constructions for an RRP kinematic chain are issued, which are called 3-dof circular tracking arc type 1 and type 2. In both types the first R joint axis is shown as a horizontal axis passing through the pivot point C and the second R joint is obtained via a circular arc in order to obtain RCM. In type 1, the P joint direction is radially directed from the connection point A of the circular arc to the pivot point C (Fig. 2a). Guerroaud and Vidal [10] present such a 3-dof circular arc manipulator for eye surgeries. Type 2 is a modified version of the type 1, such that the P joint direction is somehow tangent to the circular arc at the connection point A (Fig. 2b). Type 2 is a better option than type 1 for the scenario in Fig. 1. To our best knowledge, such a manipulator has not been used for MIS applications before.

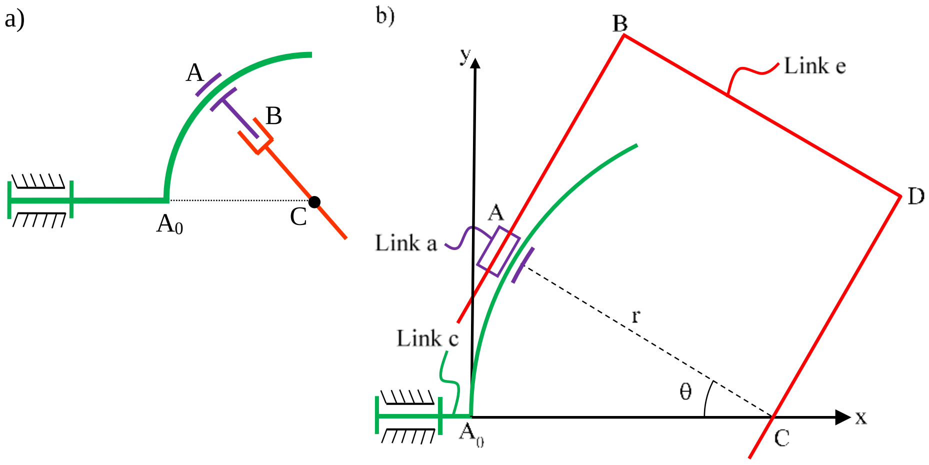

Fig. 2. 3-dof circular tracking arc a) type 1, b) type 2.

2.2 Hybrid Structures

A hybrid kinematic structure is composed of both serial and parallel sub-structures, hence possessing some advantages of both types. Possible hybrid kinematic structures can be listed as p-s-s, s-p-s, s-s-p, p-p-s, p-s-p, s-p-p, p-p-p, s-2p, 2p-s, where s is serial, p is parallel and 2p is a 2-dof parallel sub-assembly. A sample s-p-s manipulator is illustrated in Fig. 3a. The parallel subassembly for the second rotation comprising two parallelogram loops is a very well-known construction for a single-dof RCM and alternative constructions are examined in detail in [1]. A sample s-2p type manipulator is given in Fig. 3b. The two prismatic joints should have same displacements. Such a manipulator presented in [11] is developed for neurosurgery applications. A sample s-p-p manipulator is illustrated in Fig. 3c. The advantage of the parallel kinematics for the P motion is that the reciprocating mass can be balanced by using a mirror symmetrical slider-crank loop.

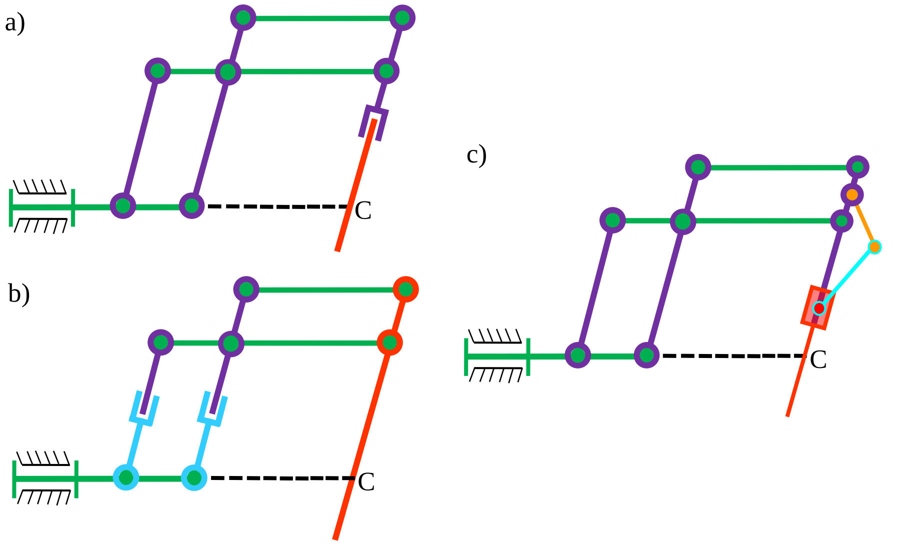

Fig. 3. Hybrid structures: a) s-p-s type, b) s-2p type, c) s-p-p type.

The p-p-p type is based on the execution of each dof via a closed loop. As an example, the manipulator in Fig. 3c can be converted into a p-p-p type manipulator if the first rotation is generated by a closed loop such as a four-bar loop. In our application, such an extra closed loop seems to be redundant. Similarly, p-p-s, p-s-s, p-s-p, 2p-s and s-s-p types do not seem to yield feasible solutions.

2.3 RCM with a Passive Joint

Besides the serial and hybrid manipulators with mechanical RCM, we also worked on some 5-dof manipulator designs with a passive RCM (pRCM). In order to obtain a pRCM, a soft part should be designed to be placed at nostril for pivoting. The passive joint at the nose tip should have 4-dof, which can be modelled as an SP (S: spherical) joint. PPPUSP and RRP(2UU)SP (U: universal joint) linkage scenarios are worked out, where the first three axes (shown with arrows in Fig. 4) could be actuated. These linkages were not considered to be feasible due to the necessity of the pivoting part to be installed at the nostril and the coupled and case-dependent relationship between the joint space and the workspace.

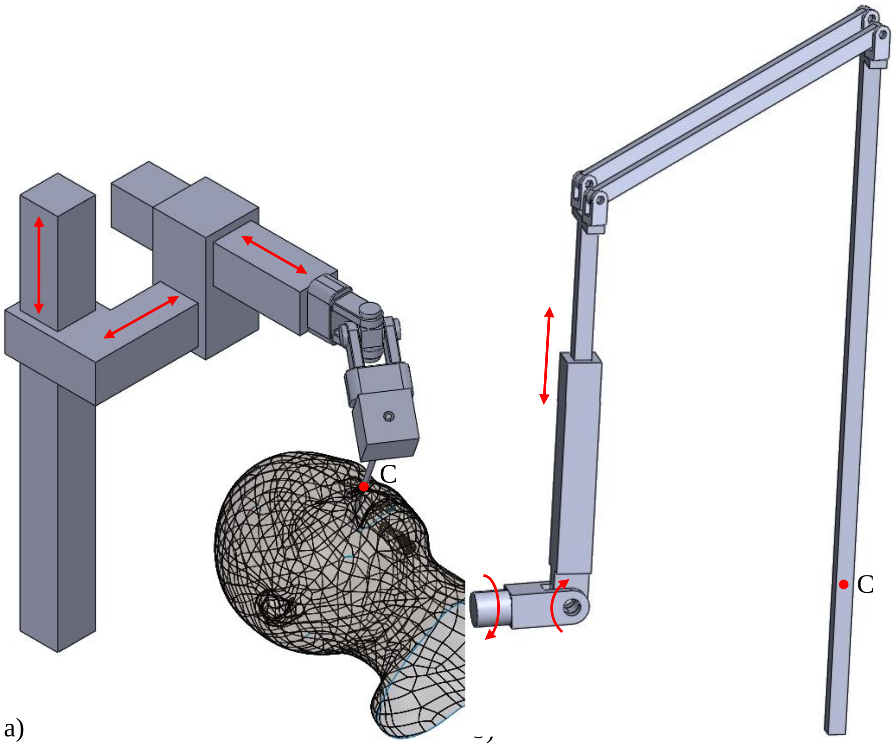

Fig. 4. a) PPPU and b) RRP(2UU) RCM manipulators with SP passive joint through point C.

3 The Solid Model of the Selected Manipulator

As the alternative manipulator structures in Section 2 are examined, the RRP circular arc type 2 manipulator (Fig. 2b) is selected for the detailed design. The solid model of the manipulator and the exploded view of the moving links are presented in Fig. 5. Motor c is located on a base frame and is connected to a series-elastic-actuator (SEA), which is connected to link c (circular link). Link a is actuated with motor a and its corresponding SEA via a cable-pulley system, such that a carriage is moved on a circular guide. Similarly, link e (end-effector) is actuated with motor e and its corresponding SEA via a cable-pulley system, such that a carriage is moved on a linear guide.

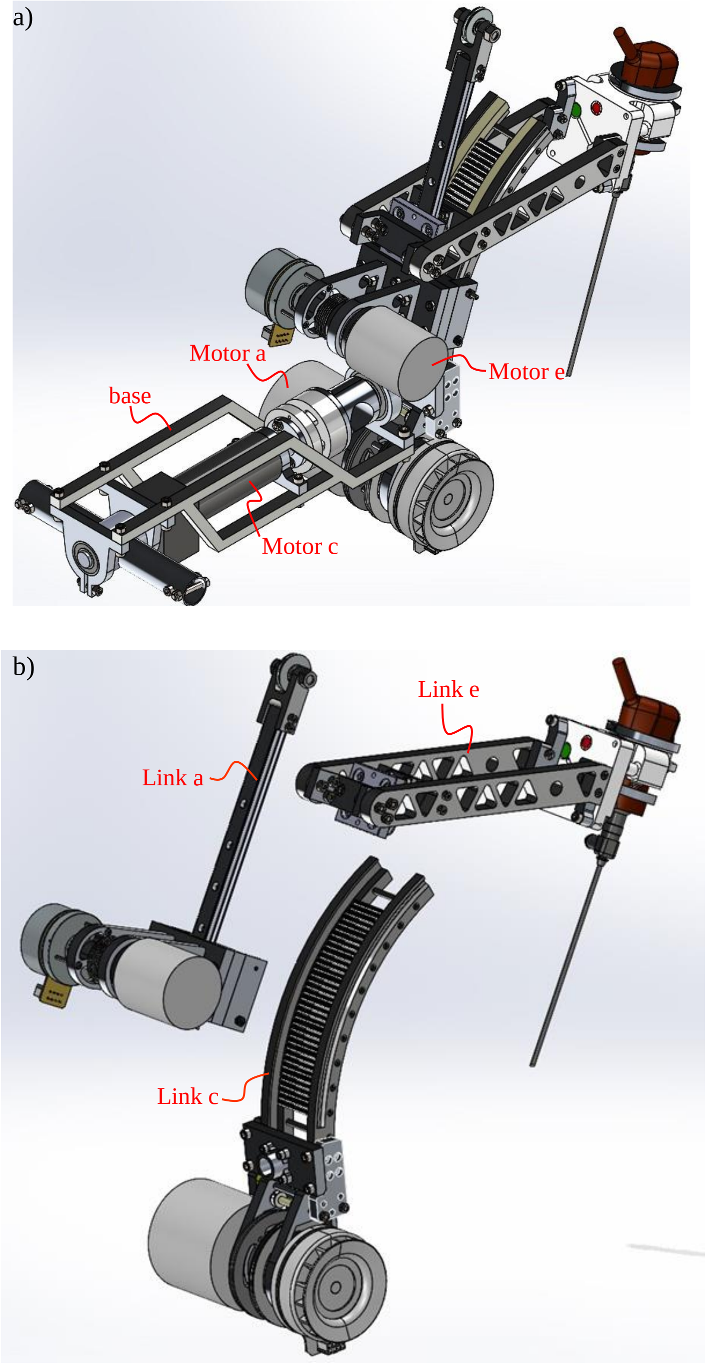

Fig. 5. a) The solid model of the RRP manipulator, b) exploded view of the moving links.

4 Gravity Balancing of the Manipulator

If the manipulator is not balanced, the weights of the links constitute most of the torque requirement from the motors, which complicates the control. Also, during an operation if the motors fail for some reason, the manipulator poses a big danger for the patient. Therefore, a mechanical solution for gravity compensation is sought.

Springs and/or counter-masses can be used for gravity balancing. After working on several solutions with balancing springs and masses, the balancing solution with counter-masses revealed as a feasible solution. In Fig. 6, the dyad OJA (links 1 and 2) and counter-mass M_{C1} are added to the manipulator to balance the mass m_a of link a at point A, such that OJAC constitutes a parallelogram. Links 3, 4, 5, 6 and counter-mass M_{C2} are added to balance the mass m_e of link e (including the endoscope) at point E, such that these links constitute a pantograph. The constructional design of link c should be such that its center-of-mass (CoM) is on its axis of rotation (x-axis).

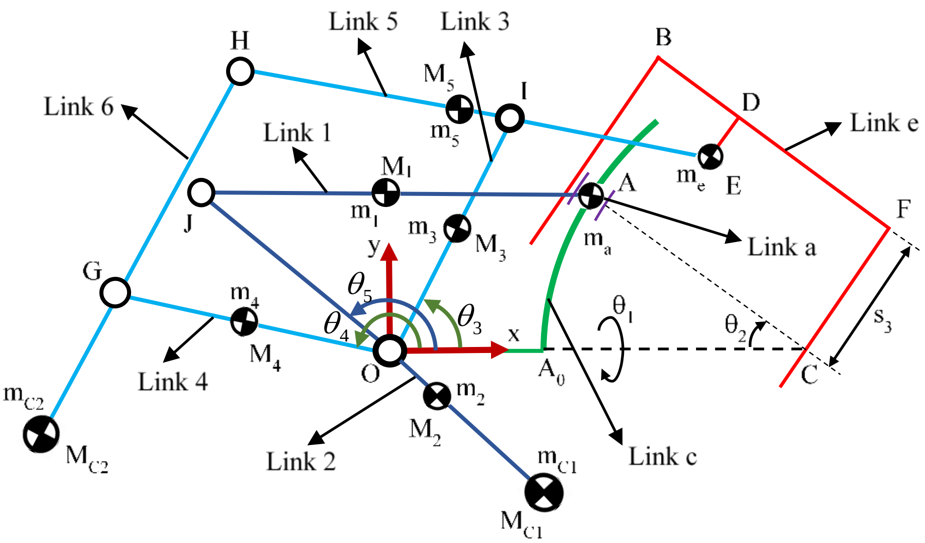

Fig. 6. Counter-mass balanced manipulator.

The CoM of the balancing links are M_i and their mass are m_i for i = 1, …, 6. Link lengths are $|JA| = |OC| = a_1$, $|JM_1| = b_1$, $|JM_{C1}| = a_2$, $|OJ| = |CA| = r$, $|OM_2| = b_2$, $|OM_{C1}| = b_{C1}$, $|OI| = |HG| = a_3$, $|OM_3| = b_3$, $|OG| = |HI| = a_4$, $|OM_4| = b_4$, $|IM_5| = b_5$, $|GM_{C2}| = b_{C2}$, $|IE| = b_e$. Following [12], the balancing equations are written as.

$$b_{C1}m_{C1} = r(m_a + m_1) - b_2m_2 \tag{1}$$

$$b_em_e = b_4m_4 + b_5m_5 + a_4m_{C2} \tag{2}$$

$$b_{C2}m_{C2} = b_3m_3 + a_3m_e \tag{3}$$

Eqs. (1)-(3) are used to design the counter mass values (m_{C1}, m_{C2}) and their CoM locations (b_{C1}, b_{C2}) when all other mass values and CoM values are determined after constructional design. The distances b_{C1} and b_{C2} are selected as long as possible such that there is no interference with their environment so that m_{C1} and m_{C2} are as small as possible. The solid model of the balanced manipulator is presented in Fig. 7. The total mass of the solid model is computed as 11.6 kg, which moves an endoscope of about 0.44 kg.

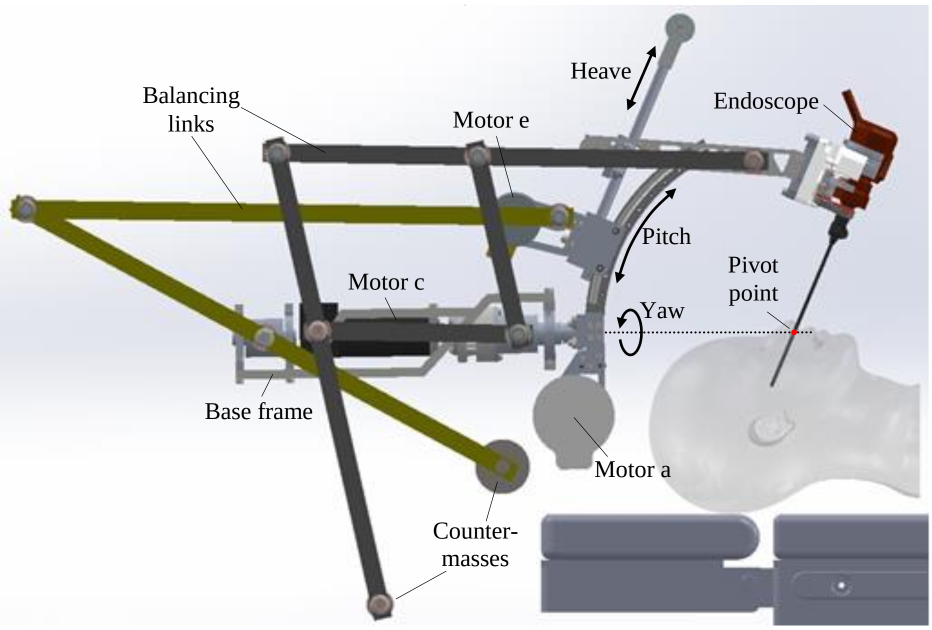

Fig. 7. Solid model of the balanced manipulator.

5 Conclusion

2R1T manipulators with RCMs for endonasal skull base surgeries are investigated in this paper. Manipulators with serial and hybrid kinematic structure and redundant manipulators with a passive joint are examined. A serial RRP manipulator with a circular arc is chosen for detailed design, where the end-effector heave motion is achieved in a tangential direction to the circular arc. The constructional design and the balancing solution for the manipulator are presented.

As future works, a prototype of the manipulator will be produced and prototype tests will be performed.

Acknowledgments

This study is financially supported by The Scientific and Technological Research Council of Turkey via grant number 219M483. We thank Eres Söylemez, M. İ. Can Dede and Volkert van der Wijk for their contributions for the structural and constructional design of the manipulator.

References

1. Zong, G., Pei, X., Yu, J., Bi, S.: Classification and type synthesis of 1-DOF remote center of motion mechanisms. Mechanism and Machine Theory 43(12), 1585–1595 (2008).
2. Kuo, C.-H., Dai, J.: Robotics for minimally invasive surgery: a historical review from the perspective of kinematics. In: Yan, H. S., Ceccarelli, M. (eds.) International Symposium on History of Machines and Mechanisms: Proceedings of HMM 2008, History of Mechanism and Machine Science Series, vol. 4, Springer, Dordrecht (2009).
3. Sadeghian, H., Zokaei, F., Hadian Jazi, S.: Constrained kinematic control in minimally invasive robotic surgery subject to remote center of motion constraint. Journal of Intelligent & Robotic Systems 95, 901–913 (2019).
4. Yaşır, A., Kiper, G., Dede, M. İ. C.: Kinematic design of a non-parasitic 2R1T parallel mechanism with remote center of motion to be used in minimally invasive surgery applications. Mechanism and Machine Theory 153, 104013 (2020).
5. Teichgräber, C., Müglitz, J., Berger, M.: Guiding linkages with remote centre of rotation for thermal cutting processes. In: Dede, M. İ. C., İtik, M., Lovasz, E.-C., Kiper, G. (eds.) Mechanisms, Transmissions and Applications: Proceedings of the Fourth MeTrApp Conference 2017, Mechanisms and Machine Science Series, vol. 52, pp. 21–30. Springer, Cham (2018).
6. Yaşır A, Kiper G (2018) Structural synthesis of 2R1T type mechanisms for minimally invasive surgery applications. In: Dede, M. İ. C., İtik, M., Lovasz, E.-C., Kiper, G. (eds.) Mechanisms, Transmissions and Applications: Proceedings of the Fourth MeTrApp Conference 2017, Mechanisms and Machine Science Series, vol. 52, pp. 31–38. Springer, Cham (2018).
7. Yaşır, A., Kiper, G., Dede, M.I.C., Van der Wijk, V.: Static force balancing of a 2R1T parallel manipulator with remote center of motion. In: Uhl, T. (ed.) Advances in Mechanism and Machine Science: Proceedings of the 15th IFToMM World Congress on Mechanism and Machine Science, Mechanisms and Machine Science Series, vol. 73, pp. 3219–3226. Springer, Cham (2019).
8. Aldanmaz, A. B., Ayit, O., Kiper, G., Dede, M. İ. C.: Gravity compensation of a 2R1T mechanism with remote center of motion for minimally invasive transnasal surgery applications. Robotica, DOI: 10.1017/S0263574722000534 (2022).
9. Dede, M. İ. C., Kiper, G., Ayav, T., Tatlıcıoğlu, E., Özdemirel, B., Maaroof, O, Ateş, G., Berker, M., Işıkay, İ, Hanalioğlu, Ş.: Cerrahın anlık yönlendirilebildiği robot yardımlı endoskop kontrol sistemi mimarisi – NeuRoboScope. In: Proceedings of the Türkiye Robotbilim Konferansı (TORK 2018), pp. 25–30. İstanbul (2010).
10. Guerrouad, A., Vidal, P.: Stereotaxical microtelemanipulator for ocular surgery. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 879–880, Seattle, WA (1989).

11. Davies, B., Starkie, S., Harris, S. J., Agterhuis, E., Paul, V., Auer, L. M.: Neurobot: A special-purpose robot for neurosurgery. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 4103–4108. San Francisco, CA (2000).
12. Van der Wijk, V.: Methodology for Analysis and Synthesis of Inherently Force and Moment-balanced mechanisms: Theory and Applications. PhD Thesis. Delft Technical University, Delft (2014).