Constrained Inverse Kinematics of Minimally Invasive Surgical Robots

Subjects: Automation & Control Systems
Contributor: Jacinto Colan

Minimally invasive surgery has undergone significant advancements, transforming various surgical procedures by minimizing patient trauma, postoperative pain, and recovery time. However, the use of robotic systems in minimally invasive surgery introduces significant challenges related to the control of the robot's motion and the accuracy of its movements. In particular, the inverse kinematics (IK) problem is critical for robot-assisted minimally invasive surgery (RMIS), where satisfying the remote center of motion (RCM) constraint is essential to prevent tissue damage at the incision point.

Keywords: surgical robot ; inverse kinematics ; constrained motion planning ; minimally invasive surgery

1. Introduction

Minimally invasive surgery (MIS) is a standard surgical procedure that reduces trauma and accelerates recovery by using long and thin surgical instruments through small incisions to access the anatomy of the patients. However, loss of direct access to the surgical workspace and the limited dexterity of conventional surgical tools impose several challenges on the surgeon, including a lack of depth perception and haptic feedback [1], which increases cognitive workload. To overcome these limitations, there has been increasing interest in the development of robotic systems for robot-assisted minimally invasive surgery (RMIS), as they enhance the surgeon's capabilities with 3D vision, dexterous surgical tools, and intuitive human–robot interfaces. Numerous robotic systems have been developed and studied in the literature. The most prominent example is the da Vinci surgical system [2], which has been widely adopted in numerous surgical rooms around the world and has performed diverse surgical procedures in different anatomical regions, such as laparoscopic, gynecological and general surgery [3]. The da Vinci surgical system employs multiple robotic arms, each equipped with a surgical instrument that accesses internal organs through trocars placed over the patient's body. However, the da Vinci surgical system has a bulky setup, entails a high cost, and the dimensions of the robotic surgical tool make it unsuitable for all types of surgery. To address these limitations, novel robotic surgical systems have been proposed for specific surgical scenarios, such as eye surgery [4], transnasal surgery [5], or pediatric laparoscopic surgery [6].

A key constraint in RMIS is the requirement for a remote center of motion (RCM), which is a constraint located at the insertion point, typically a trocar, that must always be respected. The surgical tool must pivot over the RCM, limiting its mobility to four degrees of freedom (DOFs): translational motion along the tool axis, pitch and yaw rotations, and rotational motion along the tool axis. Various strategies have been proposed to ensure the RCM constraint and can be coarsely classified as mechanical and programmable RCMs [7]. RCM mechanisms typically use structures based on parallelograms, which facilitate motion control and prevent potential hazards by ensuring the constraint of the RCM at the mechanical level [8][9]. However, mechanical RCMs have a significant limitation in their lack of adaptability, as the location of the RCM is fixed and must be aligned with the trocar placed on the patient. As a result, the placement of the robotic system, as well as the layout of the surgical room, must be adapted to accommodate the mechanical structure. Moreover, the RCM mechanism occupies a considerable amount of space above the insertion point, limiting robotic arms' range of motion and obstructing the assistant staff's access. The da Vinci surgical system [10] is an example of a passive RCM. On the contrary, programmable RCMs offer flexibility with a software-based RCM that can be dynamically adjusted without the need for additional mechanical structures, which also reduces costs. It utilizes the redundancy found in typical robotic manipulators to keep the constraint through synchronized control of the manipulator's joints. The DLR MIRO [11] is an example of a surgical robotic system that follows a programmable RCM strategy. However, this approach transforms the RCM problem into a control problem that requires real-time motion planning to solve.

2. Constrained Inverse Kinematics

Inverse kinematics is a fundamental problem in robotics, which involves determining the joint angles necessary to achieve a desired position and orientation of the end effector. For non-redundant manipulators, analytical approaches provide explicit solutions for the unconstrained inverse kinematics problem. However, when the robot has redundant degrees of freedom, the inverse kinematics problem becomes more complex, as there can be multiple kinematic solutions. Additionally, the problem can become more challenging when there are additional tasks and kinematic constraints that must be satisfied, such as obstacle avoidance or joint limits. In such cases, iterative numerical methods or optimization techniques are often used to find a suitable solution.

Constrained inverse kinematics is a critical building block for developing control strategies for robotic systems that must accomplish multiple tasks simultaneously. It has been extensively studied for various types of constraints, such as joint limits avoidance [12], obstacle avoidance [13], robot posture [14], and maximization of manipulability [15]. Kinematic redundancy, which occurs when the manipulator's degrees of freedom are greater than those required to execute a task, is often utilized to satisfy these additional constraints [16].

Analytical approaches are commonly used to solve the constrained inverse kinematics problem [17][18]. Although they can provide closed-form solutions suitable for real-time robot control, the set of constraints that analytical IK solvers can handle is limited. Additionally, analytical solvers must be designed in advance and can be susceptible to changes in robot configuration.

Numerical solvers, on the other hand, are more generic and use iterative methods based on the local Jacobian inverse until convergence to an optimal solution. Numerical IK solvers are known to be slower than analytical methods, and active research has been carried out to speed up the solving time by looking for alternatives to Jacobian inverse computation [19] or combining it with other optimization-based methods [20]. Generic constraints can be included in an optimization-based numerical approach, in which the IK problem is formulated as a general nonconvex nonlinear optimization problem and solved by iterative gradient-based nonlinear solvers [21]. This approach can handle a wide range of constraints, including nonlinear and nonconvex ones, and is suitable for a variety of robotic applications. However, it can be computationally expensive and may require careful tuning of the solver parameters to achieve the desired performance.

3. Task Prioritization

When a hierarchy exists between constraint tasks in inverse kinematics, a prioritization scheme must be followed. Each task is assigned a priority level, and high-priority tasks should not be affected by lower-priority tasks [22]. There are two main categories of hierarchical IK schemes: strict and non-strict control methods.

Strict methods assume that each task is assigned a different priority, enforcing the hierarchy by projecting consecutively joint velocities from lower-priority tasks to the null space of higher-priority tasks. Siciliano and Slotine [23] proposed a hierarchical framework to handle an arbitrary number of tasks by considering the null space projector of one task in the next task solution in priority order. Chiaverini [24] proposed a different approach for two tasks that guarantees robustness against algorithmic singularity, which is later extended to multiple tasks in [25]. Hierarchical quadratic programming (HQP) has also been explored for strict hierarchical IK, solving a quadratic programming problem hierarchically under equality and inequality constraints. HQP has been used in humanoid robots [26], robot teleoperation [27], and human–robot collaboration [28].

Non-strict methods offer a simplified approach to task prioritization by assigning weights to each task according to its relative importance. This simplification reduces computational time and allows for more flexible control over the optimization problem. However, in cases where multiple tasks have the same priority level, non-strict methods can result in ambiguity and compromise the desired priority scheme. Additionally, it is challenging to completely isolate one task from the influence of another, even when assigning vastly different weights. A critical drawback of non-strict methods is the need for fine-tuning the weight assignment for each task, which can be time consuming and require expert knowledge.

4. Constrained Inverse Kinematics in RMIS

In RMIS, the preservation of the remote center of motion (RCM) is an essential constraint that must be addressed. Typically, programmable RCM constraints are formulated as high-priority tasks within a strict hierarchical control scheme. For instance, Azimian et al. [29] proposed a method that utilizes a projection of a secondary tool pose control task in the null space of the RCM task. The RCM constraint task is described as a kinematic restriction based on the plane tangent to the patient’s skin. They experimentally validated their approach in an endoscope positioning task. However, one of the limitations of their method is the assumption of constant tool insertion depth, which may not hold throughout the surgical procedure. To overcome this limitation, Aghakhani et al. [30] proposed a variation of the previous method, which considers the tool insertion velocity as an additional control variable. They utilize an augmented Jacobian approach in which the tool pose control task and the RCM constraint task Jacobians are stacked. The pseudoinverse of the augmented Jacobian provides a solution that satisfies both tasks. However, their method does not ensure the orthogonality of both task Jacobians, which can lead to algorithmic singularities in the augmented task Jacobian [31]. Another strict hierarchical approach was proposed by Sandoval et al. [32] for a torque-controlled manipulator. In their approach, they prioritize the task of minimizing the distance between the trocar point and the surgical tool, while a secondary task is defined as the control of the tool pose. Following this approach, they were able to achieve an accurate position of the tool tip while ensuring the preservation of the RCM.

While some approaches for RCM implementations consider independent tasks in a hierarchical scheme, others aim to unify the task. For example, Osa et al. [33] introduced a zero-velocity constraint in the normal plane of the tool axis to avoid lateral movement around the RCM. Marinho et al. [34] proposed generating a trajectory by projecting the desired endoscope position from the perspective of the RCM, then computing the corresponding joint configurations for the external joints. However, these methods have limitations, including their dependence on the number of links within the patient. For example, refs. [33][34] only consider one link after the trocar point, and joint limits are not directly taken into account in the RCM formulation.

Optimization-based RCM formulations can explicitly incorporate equality and inequality constraints, making them suitable for including joint limits in the problem. In [35], Kapoor et al. proposed a weighted multi-objective constrained optimization framework that uses a sequential quadratic programming approach to solve the nonlinear constrained problem. Yang et al. [36] employed a differential evolution algorithm to solve an endoscope visual servoing optimization problem subject to an RCM constraint.

References

1. Colan, J.; Davila, A.; Hasegawa, Y. A Review on Tactile Displays for Conventional Laparoscopic Surgery. Surgeries 2022, 3, 334–346.
2. Guthart, G.S.; Salisbury, J.K. The Intuitive telesurgery system: Overview and application. In Proceedings of the 2000 IEEE International Conference on Robots and Automation (ICRA), San Francisco, CA, USA, 24–28 April 2000; pp. 618–621.
3. D’Ettorre, C.; Mariani, A.; Stilli, A.; Rodriguez y Baena, F.; Valdastri, P.; Deguet, A.; Kazanzides, P.; Taylor, R.H.; Fischer, G.S.; DiMaio, S.P.; et al. Accelerating Surgical Robotics Research: A Review of 10 Years with the da Vinci Research Kit. IEEE Robot. Autom. Mag. 2021, 28, 56–78.
4. Koyama, Y.; Marinho, M.M.; Mitsuishi, M.; Harada, K. Autonomous Coordinated Control of the Light Guide for Positioning in Vitreoretinal Surgery. IEEE Trans. Med. Robot. Bionics 2022, 4, 156–171.
5. Colan, J.; Nakanishi, J.; Aoyama, T.; Hasegawa, Y. A Cooperative Human-Robot Interface for Constrained Manipulation in Robot-Assisted Endonasal Surgery. Appl. Sci. 2020, 10, 4809.
6. Marinho, M.M.; Harada, K.; Deie, K.; Ishimaru, T.; Mitsuishi, M. SmartArm: Suturing Feasibility of a Surgical Robotic System on a Neonatal Chest Model. IEEE Trans. Med Robot. Bionics 2021, 3, 253–256.
7. Chen, Y.; Zhang, S.; Wu, Z.; Yang, B.; Luo, Q.; Xu, K. Review of surgical robotic systems for keyhole and endoscopic procedures: State of the art and perspectives. Front. Med. 2020, 14, 382–403.
8. Yaşır, A.; Kiper, G.; Dede, M.C. Kinematic design of a non-parasitic 2R1T parallel mechanism with remote center of motion to be used in minimally invasive surgery applications. Mech. Mach. Theory 2020, 153, 104013.
9. Kuo, C.H.; Dai, J.S.; Dasgupta, P. Kinematic design considerations for minimally invasive surgical robots: An overview. Int. J. Med Robot. Comput. Assist. Surg. 2012, 8, 127–145.
10. Freschi, C.; Ferrari, V.; Melfi, F.; Ferrari, M.; Mosca, F.; Cuschieri, A. Technical review of the da Vinci surgical telemanipulator. Int. J. Med Robot. Comput. Assist. Surg. 2013, 9, 396–406.
11. Hagn, U.; Konietschke, R.; Tobergte, A.; Nickl, M.; Jörg, S.; Kübler, B.; Passig, G.; Gröger, M.; Fröhlich, F.; Seibold, U.; et al. DLR MiroSurge: A versatile system for research in endoscopic telesurgery. Int. J. Comput. Assist. Radiol. Surg. 2010, 5, 183–193.

12. Moe, S.; Antonelli, G.; Teel, A.R.; Pettersen, K.Y.; Schrimpf, J. Set-Based Tasks within the Singularity-Robust Multiple Task-Priority Inverse Kinematics Framework: General Formulation, Stability Analysis, and Experimental Results. Front. Robot. AI 2016, 3, 16.

13. Mannucci, A.; Caporale, D.; Pallottino, L. On Null Space-Based Inverse Kinematics Techniques for Fleet Management: Toward Time-Varying Task Activation. IEEE Trans. Robot. 2021, 37, 257–274.

14. Mansard, N.; Khatib, O.; Kheddar, A. A Unified Approach to Integrate Unilateral Constraints in the Stack of Tasks. IEEE Trans. Robot. 2009, 25, 670–685.

15. Dufour, K.; Suleiman, W. On maximizing manipulability index while solving a kinematics task. J. Intell. Robot. Syst. 2020, 100, 3–13.

16. Chiacchio, P.; Chiaverini, S.; Sciavicco, L.; Siciliano, B. Closed-Loop Inverse Kinematics Schemes for Constrained Redundant Manipulators with Task Space Augmentation and Task Priority Strategy. Int. J. Robot. Res. 1991, 10, 410–425.

17. Berenson, D.; Srinivasa, S.; Kuffner, J. Task Space Regions: A framework for pose-constrained manipulation planning. Int. J. Robot. Res. 2011, 30, 1435–1460.

18. Diankov, R. Automated Construction of Robotic Manipulation Programs. Ph.D. Thesis, Carnegie Mellon University, Pittsburgh, PA, USA, 2010.

19. Escande, A.; Mansard, N.; Wieber, P.B. Fast resolution of hierarchized inverse kinematics with inequality constraints. In Proceedings of the 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, USA, 3–7 May 2010; pp. 3733–3738.

20. Beeson, P.; Ames, B. TRAC-IK: An open-source library for improved solving of generic inverse kinematics. In Proceedings of the 2015 IEEE-RAS 15th International Conference on Humanoid Robots, Seoul, Republic of Korea, 3–5 November 2015; pp. 928–935.

21. Dai, H.; Izatt, G.; Tedrake, R. Global inverse kinematics via mixed-integer convex optimization. Int. J. Robot. Res. 2019, 38, 1420–1441.

22. An, S.i.; Lee, D. Prioritized Inverse Kinematics: Generalization. IEEE Robot. Autom. Lett. 2019, 4, 3537–3544.

23. Siciliano, B.; Slotine, J.J. A general framework for managing multiple tasks in highly redundant robotic systems. In Proceedings of the Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments, Pisa, Italy, 19–22 June 1991; Volume 2, pp. 1211–1216.

24. Chiaverini, S. Singularity-robust task-priority redundancy resolution for real-time kinematic control of robot manipulators. IEEE Trans. Robot. Autom. 1997, 13, 398–410.

25. Mansard, N.; Chaumette, F. Task Sequencing for High-Level Sensor-Based Control. IEEE Trans. Robot. 2007, 23, 60–72.

26. Escande, A.; Mansard, N.; Wieber, P.B. Hierarchical quadratic programming: Fast online humanoid-robot motion generation. Int. J. Robot. Res. 2014, 33, 1006–1028.

27. Gholami, S.; Tassi, F.; De Momi, E.; Ajoudani, A. A Reconfigurable Interface for Ergonomic and Dynamic Tele-Locomanipulation. In Proceedings of the 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Prague, Czech Republic, 27 September–1 October 2021; pp. 4260–4267.

28. Tassi, F.; De Momi, E.; Ajoudani, A. Augmented Hierarchical Quadratic Programming for Adaptive Compliance Robot Control. In Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA), Xi'an, China, 30 May–5 June 2021; pp. 3568–3574.

29. Azimian, H.; Patel, R.V.; Naish, M.D. On constrained manipulation in robotics-assisted minimally invasive surgery. In Proceedings of the 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, Tokyo, Japan, 26–29 September 2010; pp. 650–655.

30. Aghakhani, N.; Geravand, M.; Shahriari, N.; Vendittelli, M.; Oriolo, G. Task control with remote center of motion constraint for minimally invasive robotic surgery. In Proceedings of the 2013 IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, 6–10 May 2013; pp. 5807–5812.

31. Marinho, M.M.; Harada, K.; Mitsuishi, M. Comparison of remote center-of-motion generation algorithms. In Proceedings of the 2017 IEEE/SICE International Symposium on System Integration (SII), Taipei, Taiwan, 11–14 December 2017; pp. 668–673.

32. Sandoval, J.; Poisson, G.; Vieyres, P. A new kinematic formulation of the RCM constraint for redundant torque-controlled robots. In Proceedings of the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, BC, Canada, 24–28 September 2017; pp. 4576–4581.

33. Osa, T.; Staub, C.; Knoll, A. Framework of Automatic Robot Surgery System using Visual Servoing. In Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010; pp. 1837–1842.
34. Marinho, M.M.; Bernardes, M.C.; Bo, A.P.L. Using General-Purpose Serial-Link Manipulators for Laparoscopic Surgery with Moving Remote Center of Motion. J. Med Robot. Res. 2016, 1, 1650007.
35. Kapoor, A.; Li, M.; Taylor, R. Constrained control for surgical assistant robots. In Proceedings of the 2006 IEEE International Conference on Robotics and Automation, ICRA 2006, Orlando, FL, USA, 15–19 May 2006; pp. 231–236.
36. Yang, S.; Wang, Y.; Zhao, H.; Cheng, H.; Ding, H. Autonomous Laparoscope Control for Minimally Invasive Surgery With Intuition and RCM Constraints. IEEE Robot. Autom. Lett. 2022, 7, 7934–7941.