DESIGN OF A ROBOTIC MANIPULATOR FOR MINIMALLY INVASIVE SURGERY

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by

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Dedicated to my late father, and mother whose life lessons provide me with a continuous motive force to put my efforts with firm dedication and extremely focused approach

Certificate

This is to certify that the thesis entitled **"Design of a Robotic Manipulator for Minimally Invasive Surgery"**, submitted by **Amanpreet Singh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

Date:

Prof. Jitendra P. Khatait
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Indian Institute of Technology Delhi.

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Amanpreet Singh

Abstract

With the integration of Minimally Invasive Surgery (MIS) and Robotics, the capabilities of a surgeon became far better than with MIS alone. It is learnt that a double parallelogram-based remote center-of-motion (RCM) mechanism is most widely used for the realization of MIS robots. The mechanical design of these devices needs to be improved further by addressing the problems arising because of the inevitable constraints, and refining their transmission design. During their kinematic modeling, classically, it is assumed that the opposite sides of constituting parallelograms are equal. However, in actual practice, it is not true on account of the mentioned constraints. It leads to the RCM deviation. Thus, instrument force at the entry point to the patient's body becomes non-zero and hence, degrades patient safety. Further, it is important to add that in control-based RCM mechanisms, RCM adjustment is possible using various control strategies. However, it is not feasible in mechanically constrained RCM devices. In addition, the combined use of spring and screw elements in the tendon-based actuation of such devices is missing in the literature. And, the concept of invariant tendon length demands an investigation to quantify the effect of said constraints. Furthermore, there is a need for the improvement of tendon drive design to avoid sharp bends of the tendon element. Moreover, there is a strong demand for cost-cutting design techniques. The present thesis has systematically addressed all of these issues and proposed solutions that not only enhance the device design but also offer several ways to realize an economic design. The concept of link parameters inequality and an accurate kinematic modeling technique have been introduced for the parallelogram-based RCM mechanisms. It is followed by the compliant mechanism-based design of an integrable and hysteresis-free RCM Adjustment System for mechanically constrained RCM devices. Further, a dedicated mechanism for tension adjustment has been introduced, characterized, and demonstrated. Furthermore, the effect of the prescribed constraints on the transmission design of distal DoFs has been investigated. Moreover, the present research work has adopted and enhanced the cable drive design of the proximal DoFs of the mechanism under consideration. Finally, the design of a double-parallelogram-based RCM mechanism has been revealed by incorporating the above-reported design improvements. The actuation of the devised manipulator has demonstrated its capabilities.

सार

मिनिमली इनवेसिव सर्जरी (एमआईएस) और रोबोटिक्स के एकीकरण के साथ, एक सर्जन की क्षमताएं अकेले एमआईएस की तुलना में कहीं बेहतर हो गईं। यह पता चला है कि एमआईएस रोबोट की प्राप्ति के लिए डबल पैरेललोग्राम-आधारित रिमोट सेंटर-ऑफ-मोशन (आरसीएम) तंत्र का सबसे व्यापक रूप से उपयोग किया जाता है। अपरिहार्य बाधाओं के कारण उत्पन्न होने वाली समस्याओं का समाधान करके और उनके ट्रांसमिशन डिज़ाइन को परिष्कृत करके इन उपकरणों के यांत्रिक डिज़ाइन में और सुधार करने की आवश्यकता है। उनके गतिज मॉडलिंग के दौरान, शास्त्रीय रूप से, यह माना जाता है कि समांतर चतुर्भुज बनाने की विपरीत भुजाएँ बराबर होती हैं। हालाँकि, वास्तविक व्यवहार में, उल्लिखित बाधाओं के कारण यह सच नहीं है। यह आरसीएम विचलन की ओर ले जाता है। इस प्रकार, रोगी के शरीर में प्रवेश बिंदु पर उपकरण बल शून्य नहीं हो जाता है और इसलिए, रोगी की सुरक्षा कम हो जाती है। इसके अलावा, यह जोड़ना महत्वपूर्ण है कि नियंत्रण-आधारित आरसीएम तंत्र में, विभिन्न नियंत्रण रणनीतियों का उपयोग करके आरसीएम समायोजन संभव है। हालाँकि, यह यांत्रिक रूप से बाधित आरसीएम उपकरणों में संभव नहीं है। इसके अलावा, ऐसे उपकरणों के टेंडन-आधारित सक्रियण में स्प्रिंग और स्क्रू तत्वों का संयुक्त उपयोग साहित्य में गायब है। और, अपरिवर्तनीय कण्डरा लंबाई की अवधारणा उक्त बाधाओं के प्रभाव को मापने के लिए एक जांच की मांग करती है। इसके अलावा, टेंडन तत्व के तेज मोड़ से बचने के लिए टेंडन ड्राइव डिज़ाइन में सुधार की आवश्यकता है। इसके अलावा, लागत-कटौती डिजाइन तकनीकों की मजबूत मांग है। वर्तमान थीसिस ने इन सभी मुद्दों और प्रस्तावित समाधानों को व्यवस्थित रूप से संबोधित किया है जो न केवल डिवाइस डिज़ाइन को बढ़ाते हैं बल्कि आर्थिक डिज़ाइन को साकार करने के कई तरीके भी प्रदान करते हैं। समानांतर चतुर्भुज-आधारित आरसीएम तंत्र के लिए लिंक पैरामीटर असमानता की अवधारणा और एक सटीक गतिज मॉडलिंग तकनीक पेश की गई है। इसके बाद यांत्रिक रूप से बाधित आरसीएम उपकरणों के लिए एक एकीकृत और हिस्टैरिसीस-मुक्त आरसीएम समायोजन प्रणाली का अनुपालन तंत्र-आधारित डिज़ाइन आता है। इसके अलावा, तनाव समायोजन के लिए एक समर्पित तंत्र पेश किया गया है, चित्रित किया गया है और प्रदर्शित किया गया है। इसके अलावा, डिस्टल डीओएफ के ट्रांसमिशन डिजाइन पर निर्धारित बाधाओं के प्रभाव की जांच की गई है। इसके अलावा, वर्तमान शोध कार्य ने विचाराधीन तंत्र के समीपस्थ डीओएफ के केबल ड्राइव डिज़ाइन को अपनाया और बढ़ाया है। अंत में, ऊपर बताए गए डिज़ाइन सुधारों को शामिल करके एक डबल-समानांतर चतुर्भुज-आधारित आरसीएम तंत्र का डिज़ाइन सामने आया है। तैयार किए गए मैनिपुलेटर के क्रियान्वयन ने इसकी क्षमताओं का प्रदर्शन किया है।

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Abbreviations

AO	**A**nalytically **O**btained
CTP	**C**apstan **T**hread **P**itch
CCW	**C**ounter **C**lockwise **D**irection
CMM	**C**oordinate **M**easuring **M**achine
D-H	**D**enavit and **H**artenberg
DoFs	**D**egrees of **F**reedom
DoF	**D**egree of **F**reedom
EDM	**E**lectric **D**ischarge **M**achine
FEA	**F**inite **E**lement **A**nalysis
LPE	**L**ink **P**arameters **E**quality
LPI	**L**ink **P**arameters Z **I**nequality
MSW	**M**easured in **S**olidWorks **E**nvironment
MEMS	**M**icro-electromechanical **S**system
MIS	**M**inimally **I**nvasive **S**urgery
MTA	**M**echanism for **T**ension **A**djustment
PLA	**P**olylactic **A**cid
RAMIS	**R**obot-**A**ssisted **M**inimally **I**nvasive **S**urgery
RCM	**R**emote **C**enter-of- **M**otion
RMS	**R**oot **M**ean **S**quare
SSRDJ	**S**econdary **S**pring **R**otation **D**ecoupling **J**oint
IWRC	**I**ndependent**W**ire **R**ope **C**ore
WSC	**W**ire**S**trand **C**ore
3D	**T**hree **D**imensional

Symbols

$\mathbf{A}_j^i$	Homogeneous transformation matrix (4×4)
$\mathbf{A}_{IRCM}^0$	Kinematic model of the ideal/theoretical RCM
$\mathbf{A}_{DRCM}^0$	Kinematic model of the deviated RCM
A_c^{pr}	Cross-sectional area of the primary cable
A_c^{sr}	Cross-sectional area of the secondary cable
a_{RCM}	distance between frames f_{4a} and f_{4a} measured along x_{RCM}
$\mathbf{B}_{DT}^0$	Kinematic model of the deviated surgical end-effector tip
d	Input displacement to the MTA
d_{ij}	Distance between points O_i to O_j
D_{0i}	Vertical distance from the i^{th} link axis to the lever rotation center
d_{ij^v}	Vertical distance between O_i to O_j
E	Young's Modulus of flexure material
E_c^{pc}	Young's Modulus of primary cable
ϵ_3	Structural angle of the RCM mechanism
f_i	i^{th} frame attached to the i^{th} link
F_i	Force at the lever input (point A) i.e. end attached to the secondary cable
F_o	Force at the lever output (point O_3') i.e. end carrying tensioning pulley P_3
F_{sr}^s	Secondary spring force
j_{i+1}	$(i+1)^{th}$ joint of the RCM mechanism
k_s^{pr}	Stiffness of the primary spring
k_s^{sr}	Stiffness of the secondary spring
k_c^{pr}	Stiffness of the primary cable
k_s^{sr}	Stiffness of the secondary cable
l	Flexure length
ℓ	Length of the secondary cable passed over the pulley P_4
L_i	i^{th} link of the considered RCM mechanism, i=0 to 8

$\mathcal{L}_i^{pr}$	Initial deformed/undeformed length of the primary cable
$\mathcal{L}_f^{pr}$	Final length of the primary cable
$\mathcal{L}_{fs}^{pr}$	Free length of the primary spring
$\mathcal{L}_{c0}^{pr}$	Undeformed length of the primary cable
$\mathcal{L}_a^{pr}$	Length of the primary elements arrangement
$\mathcal{L}_{c0}^{sr}$	Undeformed length of the secondary cable
$\mathcal{L}_c^{pr}(\phi)$	Lenght of the primary cable between pulleys P_1 and P_2
$\mathcal{L}_p^{sr}$	Lenght of the secondary cable passed over pulley pulley P_4
$\mathcal{L}_a^{pr}(\phi)$	Lenght of the primary elements arrangement excluding $\mathcal{L}_c^{pr}(\phi)$ and $\mathcal{L}_c^{pr}(\phi_i)$
N_{ie}	Number of the link parameter inequalities
N_p	Possible combination of the inequalities
N_w	Number of ways in which the RCM can deviate
n	Factor of safety
$\mathbf{r}$	Joint vector for base parallelograms
r_p	Pulley radius
r_o	Radius of lever rotation at point $O_{3'}$
r_i	Radius of lever rotation at point A'
$\mathbf{S}_y$	Tensile strength in yield
S_0^{pr}	Initial tension of the primary spring
S_0^{sr}	Initial tension of the secondary spring
T	Total tension in the primary cable
T_{c0}^{pr}	Initial tension in the primary cable
T_s	Supplemental tension generated by the MTA
t	Flexure thickness
w	Flexure width
μ_i	Increase in the wrap angle over pulley P_i, i=1, 2
ν	Poisson's ratio
ν_i	Wrap angle over pulley P_i for d=0, i=1, 2
ϕ	Lever rotation angle
$\Delta\phi$	Change in the lever angle
δ_{s0}^{pr}	Initial deformation of the primary spring
δ_{s0}^{sr}	Initial deformation of the secondary spring
δ_s^{pr}	Deformation of the primary spring
δ_s^{sr}	Deformation of the secondary spring
δ_c^{pr}	Deformation of the primary cable

δ_c^{sr}	Deformation of the secondary cable
θ_l	Excluded angle of the lever
θ_q	i^{th} joint variable of the considered RCM mechanism, q= 1 to 8
α	Primary cable angle on the right-hand side of the pulley P_3
β	Primary cable angle on the left-hand side of the pulley P_3
γ	Secondary cable angle
ψ	Angle of the lever segment O_0O_3
η	Lever output force vector at $O_3^{'}$
ψ_w	Wrap angle of the primary cable over pulley P_3
κ_1	Angle between horizontal and the line joining pulleys P_1 and P_5
κ_2	Angle between horizontal and the line joining pulleys P_2 and P_6
ρ_1	Angle between the routed cable and the line joining pulleys P_1 and P_5
ρ_2	Angle between the routed cable and the line joining pulleys P_2 and P_6