Kinematics Analysis of 6-DOF Parallel Micro-Manipulators with Offset U-Joints: A Case Study

Mohsen Moradi Dalvand, Monash University, Australia
Bijan Shirinzadeh, Monash University, Australia

ABSTRACT

This paper analyses the kinematics of a special 6-DOF parallel micro-manipulator with offset RR-joint configuration. Kinematics equations are derived and numerical methodologies to solve the inverse and forward kinematics are presented. The inverse and forward kinematics of such robots compared with those of 6-UCU parallel robots are more complicated due to the existence of offsets between joints of RR-pairs. The characteristics of RR-pairs used in this manipulator are investigated and kinematics constraints of these offset U-joints are mathematically explained in order to find the best initial guesses for the numerical solution. Both inverse and forward kinematics of the case study 6-DOF parallel micro-manipulator are modelled and computational analyses are performed to numerically verify accuracy and effectiveness of the proposed methodologies.

Keywords: Degree of Freedom (DOF), Forward Kinematics, Inverse Kinematics, Kinematic Chain, Parallel Manipulators

1. INTRODUCTION

Due to advantages of parallel manipulators over manipulators with serial kinematics chains, they are commonly used in various industrial and research applications. Positioning errors in serial kinematic chains propagate throughout the chain links, while this is not the case in parallel kinematic chains (Tian, Shirinzadeh, Zhang, & Alici, 2009). Furthermore, parallel structures inherently distribute the forces/torques by the actuators providing this class of robots with high bandwidth dynamic characteristics (Alici & Shirinzadeh, 2006). The parallel structure was originally proposed in Gough machine for testing the tires of the airplane (Gough, 1956) and in Stewart machine as a flight simulator (Stewart, 1965). Thereafter, certain parallel architectures with more potential applications in robotics were developed (Hunt & Primrose, 1993). In the past two decades, parallel manipulators have received considerable research attentions and efforts due to the variety of practical applications. General applications of this kinematics configuration include flight simulators (Salcu-
dean, Drexel, Ben-Dov, Taylor, & Lawrence, 1994; Stewart, 1965); shaking tables used to investigate the effects of earthquakes in building structures; support structures for micro/nano-positioning; industrial robots for high speed assembly (Cleary, Brooks, & Hughes, 1993); force and torque sensors (Kerr, 1989); parallel kinematic machines (Zhao, Fang, Li, Xu, & Zhang, 1998); minimally invasive surgery instruments and even entertainment devices (Merlet, 2006). Parallel architectures were widely investigated and utilised in flexure based mechanisms for micro/nano manipulations (Asif & Iqbal, 2011; Liaw, Shirinzadeh, & Smith, 2008b; Tian, Shirinzadeh, & Zhang, 2009) and for frontier applications such as scanning electron microscopy, atomic force microscopy, cell surgery, nano surgery, and micro/nano surface methodology (Li & Xu, 2009; Liaw, Shirinzadeh, & Smith, 2008a; Yi, Chung, Na, Kim, & Suh, 2003). Parallel manipulators have also been developed for large workspace providing macro/micro manipulation capabilities (Alici & Shirinzadeh, 2006; Portman, Sandler, & Zahavi, 2000). Further, parallel micro/nano manipulators may be integrated with parallel macro/micro manipulators through accurate reconfigurable fixturing techniques (Zubir, Shirinzadeh, & Tian, 2009). This will enable large workspace envelope providing coarse to ultra-precision positioning of an end-effector like a surgical tool (Moradi Dalvand & Shirinzadeh, 2011d; Shoham et al., 2003).

Research efforts have also been directed toward utilisation of the parallel robots in medicine applications (Narayanan, Kannan, Zhou, Mendel, & Krovi, 2011) and surgery operations including laparoscopic surgery (Li & Payandeh, 2002), bone surgery (Shoham et al., 2003), and eye surgery (Nakano, Sugita, Ueta, Tamaki, & Mitsuishi, 2009). With the Evolution I precision robot, a new neurosurgical tool has become available for the precise steering of instruments within the cranium. This system was used for neuronavigation in endoscopic procedures (Zimmermann, Krishnan, Raabe, & Seifert, 2002, 2004). RSPR3, a compact and lightweight robot was designed and constructed for knee arthroscopic surgery and as an integrated tool for registration and surgical assistance in total knee replacement surgery (TKR) (Malvisi, Fadda, Valleggi, Bioli, & Martelli, 2001). A parallel mechanism on a dexterous micromanipulation system was developed for use in assembling micromachines, manipulating biological cells, and performing microsurgery (Tanikawa & Arai, 1999). A compact parallel robot (CRIGOS) for image-guided orthopedic surgery was proposed with a modular system comprising of a compact parallel robot and a software system for planning surgical interventions and for supervision of the robotic device (Brandt et al., 1999). A micro robot called MIPS with a parallel mechanical architecture having 3-DOF was developed to allow fine positioning of a surgical tool (Merlet, 2001). The purpose of MIPS was to act as an active wrist at the tip of an endoscope, and provide an accurate tool to the surgeon that may further offer a partial force-feedback. Another 6-DOF parallel manipulator called MiniAture Robot for Surgical procedures (MARS) was developed which is a $5 \times 7$ (cm$^2$), cylinder, weighing 200 (g) (Shoham et al., 2003). It can be used in a variety of surgical procedures requiring precise positioning and orientation of a handheld surgical robot in the vicinity of a rigid bony structure. A medical parallel robot applicable to chest compression in the process of cardiopulmonary resuscitation was proposed that is a 3-PUU translational parallel manipulator (Li & Xu, 2007). Finally a 6-DOF parallel surgical robot for precise skull drilling in stereotactic neurosurgical operations was developed that is $35 \times 35 \times 45$ (cm$^3$), weighting about 6(kg) (Tsai & Hsu, 2007).

In addition to utilisation of parallel robots in surgery, hybrid serial-parallel architectures have also been proposed in order to obtain the advantages of parallel and serial architectures together making them able to have accurate positioning over large workspace. Successful preliminary results were obtained by using a serial-parallel robotic system composed of a Puma 562 and CaPaMan2 (Cassino Parallel Manipulator 2) (Aguirre, Acevedo, Carbone,
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