Design and Motion Control of a 6-UPS Fully Parallel Robot for Long Bone Fracture Reduction

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ABSTRACT

The incidences of long bone fractures in New Zealand are approximately 1 in 10,000. Long bones such as tibia and femur have complicated anatomic structures, making the realignment of these long bone fractures reliant on the skill of the surgeon. The drawbacks of current practice result in long time exposure to radiation, slow recovery and possible morbidity. A semi-automated long bone fracture reduction system based on a 6-DOF parallel robot platform has been in development since 2004.

The developed 6-DOF parallel robot platform comprises of six linear actuators with rotary incremental encoders. To implement a realignment of long bone fractures, a framework for the 6-DOF platform robot has been developed. The inverse kinematics and singularity of the 6-DOF parallel robot has been studied to obtain the actions and Jacobin matrices.

In motion control a multiple axis motion controller and amplifiers were used for 6-DOF parallel robot. PID tuning algorithms were developed based on the combination of the general tuning result and the contour control principle. The PID parameters have been validated by a numbers of experiments.

The practical realignment of bone fractures requires a "Pull-Rotate-Push" action implemented by the 6-DOF parallel robot. After calibration, the reduction trajectories were generated accurately. The actual trials on the artificial fractures have shown that the robot developed is capable of performing the required reduction motion.

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1.1 Introduction

1.1.1 Definition

A long bone fracture realignment medical robot system is under development at Massey University in Auckland. This robot system is expected to be a semi-automated fracture reduction system interacting with a Human-Machine (HM) interface. After planning and simulation through HMI in an offline mode, the repositioning movements planned by the surgeon will be performed on a robot platform whose end-effector is attached to the patient's foot. With the aid of this system, an actual manipulation of the fracture fragments will become more accurate, safe and more efficient compared with current manual procedures. The old system relies on the surgeon's experience and ability to interpret X-rays, a higher volume of X-ray exposure rate on the patients, higher risk possibility of other infections, human fatigue and lengthy operations.

1.1.2 System structure

The fracture realignment procedures consist of a planning phase (or teaching) and an operational phase. According to these two phases, the entire system has been developed as shown in Figure1.1 (Graham et. al., 2005).

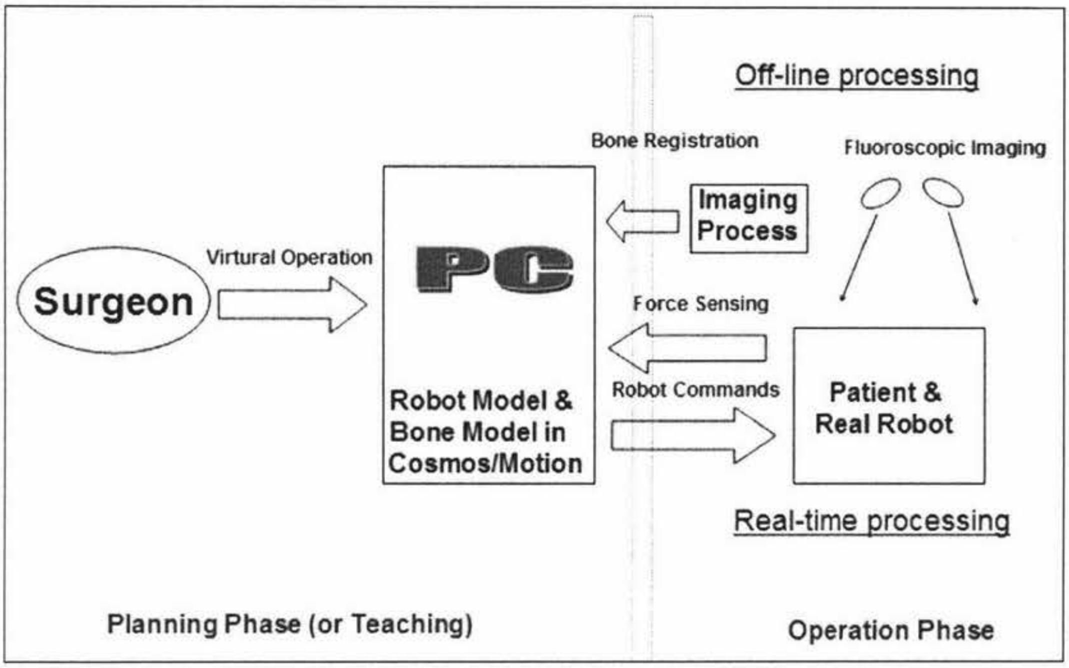

Figure 1.1 Overview of the proposed system structure

To achieve the required robot system, the following functional modules should be developed.

System modeling & software engineering is the primary module, which integrates the other subsystems for signal inputting, motion analysis, trajectory generation, motion implementation, feedback and emergency procedures.

X-ray Image processing for geometric model of fractures is to take advantage of existing digital fluoroscopic images to reconstruct fractures in a three-dimensional environment. An effective procedure is required to reduce fluoroscopic images taken, and the format of the relative displacement of fractures needs to be represented in homogenous transformations.

Motion implementation emphasizes that a compact/portable 6-DOF (Degree-Of-Freedom) parallel robot is used to provide spatial mobility for fracture reduction. The frame of robot, formation, kinematics and dynamics analysis are required to manipulate the fractures realignment in a controlled fashion.

Human machine interface for surgeons differs from an engineer's requirements. A software environment is required to be developed for surgical procedures, in which the geometric fractures can be modeled from X-ray images, and the fractures' biomechanics and robotic dynamics can be visualized, simulated and animated. A graphical user interface (GUI) for the surgeon's convenience of planning and decision making is essential.

1.1.3 Project aim

This thesis is concerned with the motion implementation of a standardized 6-DOF parallel robot for the use in the surgical environment. In 2004, a 6-DOF parallel Stewart-Gough platform was introduced into this project. This Stewart Gough platform comprises of six linear actuators attached between a top and base plate. The ends of each linear actuator are equipped with a 3-DOF joint and a 2-DOF joint. In principle, the linear extension and retraction of the six actuators gives the platform six degrees-of-freedom positioning capabilities, consisting of three translational and three rotational degree-of-freedoms (Harib and Srinivasan, 2003).

This platform was constructed and single motor was tested. As a platform, it was not working in a control fashion. The trial and evaluation of the prototype system did not begin in a real operation theatre environment, the robot framework in term of real environment was missing and the analysis of the kinematics and performance was not completed. All these issues are required to be studied deeply before the platform would get into a working system. In view of this, this project was aimed to work out the solution for these issues clearly and provide more valuable experiences and sources for the future system integration.

1.2. Background

1.2.1 The current bone realignment procedure

The initial requirements of the robot were specified by a surgeon, who hoped Massey University to develop a robot system for image-guided orthopedic surgery. The surgical procedure is described as below.

The patient's foot is attached to a traction machine connected to the patient's table through a 2-DOF linkage. The traction machine is able to slide along one of links to adjust linear displacement according to patient leg length and has the purpose of pulling the broken bone fragments into partial alignment. This is the main method of realigning during the operation (Figure1.2).

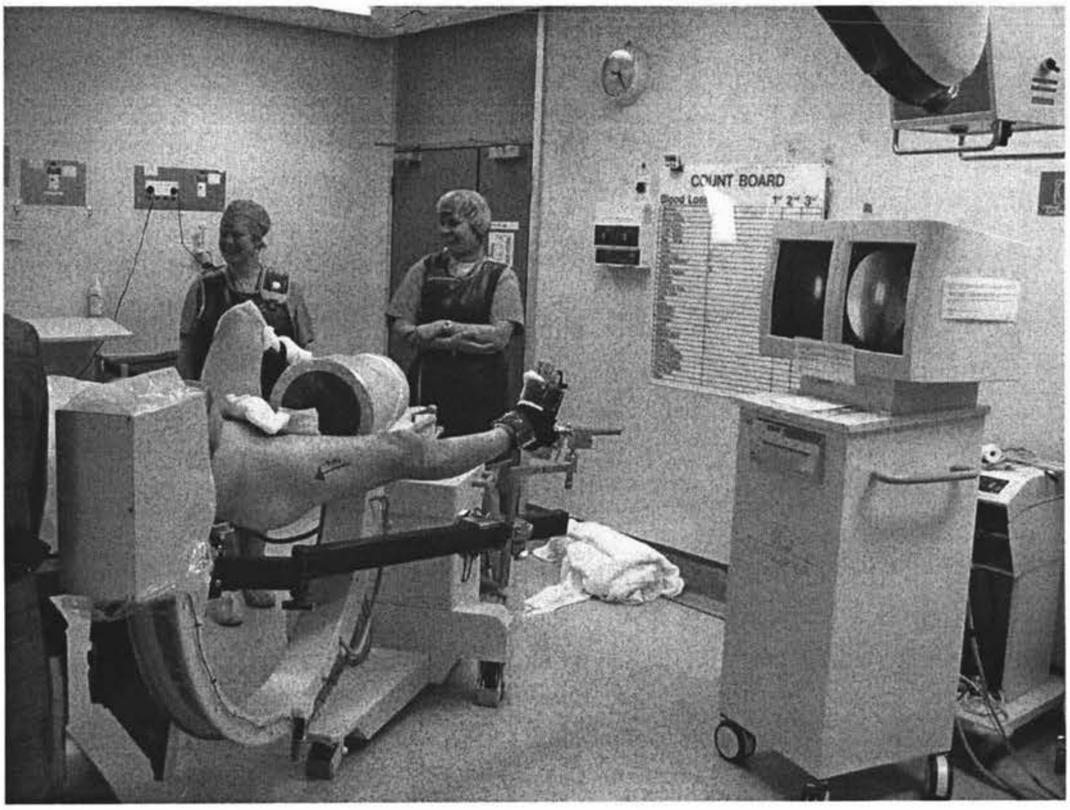

Figure 1.2 Long bone fracture realignment operation

The alignment of the broken bones is viewed in real time using a fluoroscope that is the large cylindrical instrument with a low power portable x-ray machine that can take short burst images that provide a video display of the position of the broken bone fragments to surgeons during the operation. Using resource provided by fluoroscope, the surgeon manipulates the broken bones manually to achieve the best possible realignment. The feedback is acted on manually by the surgical assistants to align the bone parts back into the best possible alignment. Once aligned, the surgeon pins the bones into position and the operation is complete. After the operation the patient's leg is placed in a cast.

The traction machine has a rack and pinion mechanism that provides the axial force to pull the leg. The foot is attached to the foot holster and the traction machine assembly is rigidly attached to the operating table (Figure 1.3).

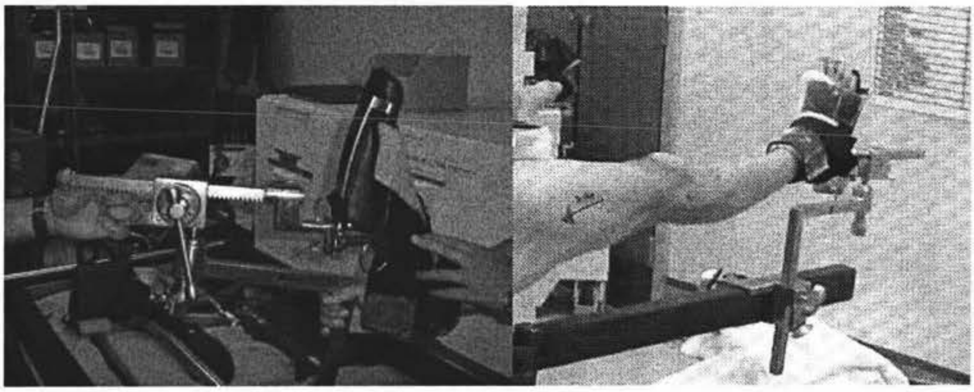

Figure 1.3 Traction machine and operation

1.2.2 Contribution by preceding students

In the past three years, a number of undergraduates have contributed to the project to various extents. Swanson (Swanson 2004) designed in SolidWorks model and built 6-DOF parallel robot. Torrance (Torrance 2004) developed a motion control system and tried on single actuator closed loop control. Ashish (Ashsih 2005) built a Hall-effect position sensor for the actuators.

1.2.3 Objectives

In early 2006, it was expected that the robot prototype should perform facture alignment procedures in a controlled fashion in the real environment and the performance of platform would be evaluated after experimentation.

To this end, objectives were identified as follows,

- Investigation and improvement of the existing design
- Design and building of a physical framework where the robot is attached
- Interfacing sensors to the motion controller
- PID tuning with effective load for all six actuators

- Trajectory generation and implementation by the robot within predefined error limitations
- Platform demonstration and simulation
- Performance evaluation and analysis
- Trouble shooting and future improvement