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Towards Miniaturised Collaborative Haptic Robots for Computer Aided Knee Surgery: Signature Robot

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Abstract

This paper describes Signature Robot, a cooperative haptic robot for knee surgery. Designed to address the lessons learned from the pioneering Acrobot Company ltd, this novel platform allows low and even impedance motion across 3 degrees of freedom, whilst the implementation of active constraints ensures patient safety throughout surgery. The robot was demonstrated to have an average positional accuracy of 0.82mm.

1 Introduction

Imperial College London's first venture into orthopaedic robotic surgery was with a spinoff company called Acrobot Ltd. This was developed over many years, culminating in a series of uni-condylar knee replacement (UKR) surgery operations with excellent results [1]. Much was learned from this experience with many hardware iterations culminating in a trolley based cooperative system with 3 powered axes carrying a cutter that required large arm motions.

To exploit the resulting know-how, Signature Robot Ltd, was founded. The Signature Robot is also cooperative, with the cutter motor being held between the fingers while the wrist is supported comfortably on a platform. This gives excellent synergy, combining the sensitive finger control of the surgeon with the precision and safety constraints ('active constraints' [2]) of the robot. The small, light robot is clamped on a simple passive arm, as seen in Figure 1, which can be readily repositioned to access regions of the knee, e.g., the tibia and femur.

This paper presents the design for Signature Robot and how it addresses the limitations of the ACROBOT, end effector positional accuracy is then quantified using a kinematic calibration routine.

2 Methods and Materials

The development of the ACROBOT gave rise to considerable insights. Initially, various gross positioning systems were developed to deal with the large cutting forces experienced in total knee replacement (TKR). It was only when unicondylar knee replacement was developed that the limited bone removal and low cutting forces allowed for the use of a smaller trolley-mounted robot adjacent to the OR table. A 3 axes powered arm, carrying a passive orientation device that held a cutting burr, allowed registration of the robot to the patient to carry out the preoperative CT scan-based plan. The results of a small clinical trial demonstrated the improved accuracy of the robot compared to experienced surgeons using conventional minimally invasive surgery (MIS) [1]. The gains of using active constraints to ensure safety of the cooperative robot were also demonstrated [3].

Benefiting from the ACROBOT experience, the patented Signature Robot has been designed with a miniaturised parallel wrist mechanism, enabling 120° motion across pitch and yaw, as shown in Figure 2a, based on the mechanics of differential gears. The parallel system offers a threefold improvement over the serial manipulator of the original ACROBOT. Firstly, it provides identical impedance across pitch and yaw due to the parallel nature. Secondly, the two motors contribute to the force output equally, leading to the incorporation of smaller motors to output the same force. This miniaturisation achieves a reduction in the inertia and thus the impedance of the platform, significantly reducing perceived impedance when back-driving. The Signature Robot can also traverse 100mm along a linear axis of minimal impedance due to the integrated high precision linear bearings.

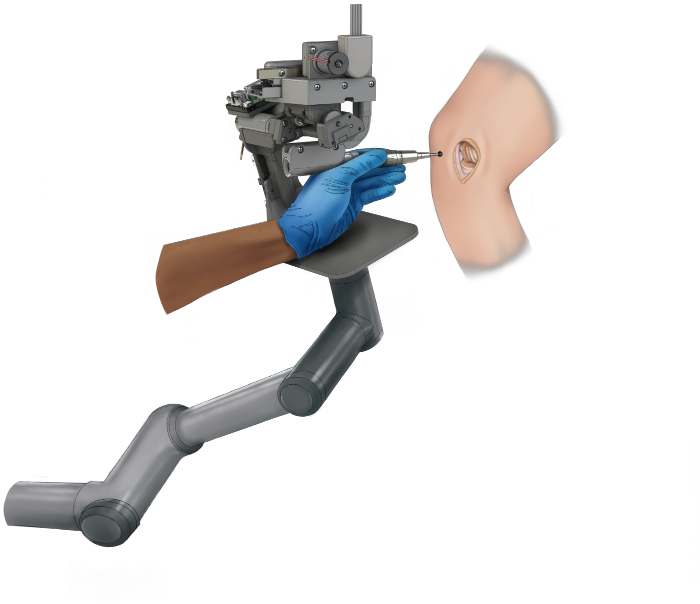


Figure 1: Signature robot with passive arm and patient

The working volume of the ACROBOT exceeded what was necessary for knee replacement surgery. Conversely, the working volume of the Signature Robot was designed with the purpose of performing UKR. Despite the small size of the robot there is no reduction in joint dexterity. Combining this design with the low impedance mechanism has allowed the Signature Robot to provide precise and dexterous finger-based movements to manipulate the end effector. The Signature Robot has also incorporated a 6 degree-of-freedom force/torque sensor between the operator's hand and the robot, as seen in Figure 2a. This placement permits new feed-forward algorithms to aid the desired motions, as well as the prerequisite active constraints implementation.

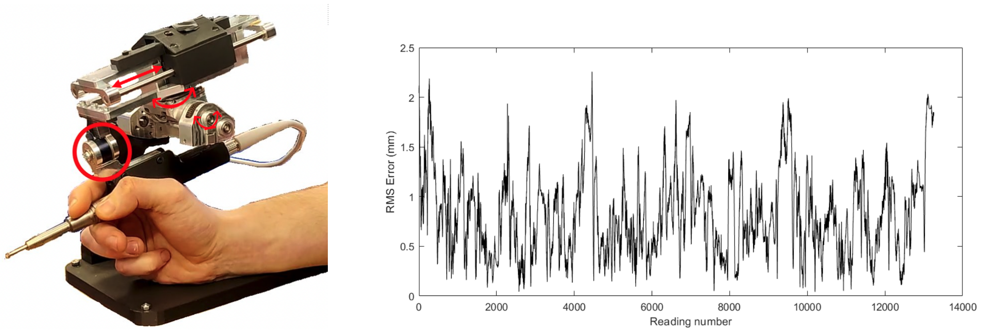
Registration and repositioning of the ACROBOT was a cumbersome procedure. The Signature Robot will incorporate a markerless registration and real-time tracking platform [4]. Furthermore, it will be mounted on a passive gross positioning system, shown in Figure 1, that can be locked when the robot has ideally positioned with respect to the patient. This reduces the complexity, size and cost of the platform.

The benefits of Signature Robot over the ACROBOT have been presented here in terms of size, workspace volume, ease of repositioning and registration. Further validation was performed to quantify the accuracy of the manufactured setup. An optical tracker (fusionTrack 500, Atracsys, Switzerland) was employed to compare the true position of the end effector with the position obtained by the motors. The forward kinematics of the robot include 13 fixed parameters that describe the kinematic geometry. The regression algorithm implemented converged these design parameters from the computer aided design (CAD) model to their true values.

3 Results

Through kinematic calibration, the errors along the manufactured platform were explored. The culmination of individual errors allowed for a total positional error estimation of the end effector. This error has been plotted in Figure 2b. Ultimately, the mean positional RMS error of Signature Robot was calculated to 0.82 mm.

The robotic platform also boasts a reduced footprint of 150x140x150mm and weighs less than 2kg. The control system is capable of providing haptic feedback forces at the tool tip of up to 25N in the three axes whilst running a haptic control loop at 500Hz.



(a) Degrees of freedom and integrated force sensor (circled)

(b) RMS Error (mm) across 13000 readings during kinematic calibration

Figure 2: Signature Robot

4 Discussion

Since the clinical introduction of the ACROBOT 20 years ago, the benefits of incorporating highly accurate, robotic assisted techniques in surgery have been constantly increasing. The Signature Robot now offers a significant footprint reduction compared to other orthopaedic robots, while also offering equal, minimal impedance across the 3 axes. By using the passive positioning arm the range of the system has increased, while also making robot repositioning in the operating room more convenient. The robot has been shown to have an end effector accuracy of 0.82 mm, this is an ideal first step in introducing the Signature Robot for cadaveric testing. Further optimisations to the design will only decrease this error further. Lastly, the integration of a new vision system will allow for real-time tissue registration, thus eliminating the need for the relatively time-consuming registration process that the ACROBOT suffered from.

Future work will explore dissipative active constraint algorithms such as frictional constraints [5]. Two separate vision platforms will be incorporated in the robotic platform. One will allow for accurate, on-the-fly patient tissue registration and soft tissue tracking [4]. The second platform will allow for the identification of common surgical tools during operation, and subsequently will ensure that no collision occurs between robot and external agents.

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