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Digitization of a manually adjustable hexapod to enhance surgical safety and accuracy

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Abstract: Precise drilling in the cranial bone, such as for minimally invasive cochlear implantation surgery, requires a level of accuracy that exceeds unaided human capabilities. One potential class of assistance devices are micro-stereotactic frames, whose core elements are patient-specific drill jigs. The customization of these jigs is the most accuracy-critical step and therefore demands a highly precise auxiliary device. Although surgical robots can meet these requirements, their high cost may limit widespread adoption. We propose an enhanced hexapod system that retains manually adjustable struts but incorporates absolute linear encoders, providing higher pose-setting accuracy and, consequently, improved surgical safety.

I. Introduction

Minimally invasive access to deep structures of the lateral skull base, such as the human inner ear in cochlear implant surgery, requires highly accurate drilling of at least one borehole. This demanding task calls for surgical assistance devices that support the surgeon and overcome human limitations in navigation and precise pose setting of the drill in order to follow a previously planned patient-specific trajectory. Surgical robots [1, 2] and micro-stereotactic frames [3, 4] have been described as potential solutions to this challenge in medical engineering.

The latter class of devices requires customization of a drill jig that serves as a rigid guide for the drill bit along the trajectory. In the case of the experimental "GluingJig" system [4, 5], three disposable components are adhesively bonded to form the final patient-specific configuration of the jig. This approach shifts the accuracy-critical task away from the actual drilling procedure in the skull towards the fabrication of an individual jig outside the situs. This relocation necessitates the use of a highly precise auxiliary device to support the surgical staff, as the purely manual gluing of the separate parts in the desired configuration cannot provide the required level of accuracy.

In its previous version, the auxiliary device used for aligning the separate parts of the drill jig was a passive Gough–Stewart platform with six manually adjustable prismatic joints. As shown in Figure 1a, each joint included a micrometer screw for fine adjustment, requiring accurate reading of a rotating vernier scale. Manual reading of this "analog" length scale was identified in previous experiments as a main source of crucial pose-setting errors [4], which could lead to serious complications in the case of a clinical application of such a device.

In this work, we present an enhanced version of the auxiliary alignment device featuring integrated length-sensing technology (Fig. 1b, c), enabling real-time digital readout of the six prismatic joint lengths for improved accuracy and safety.

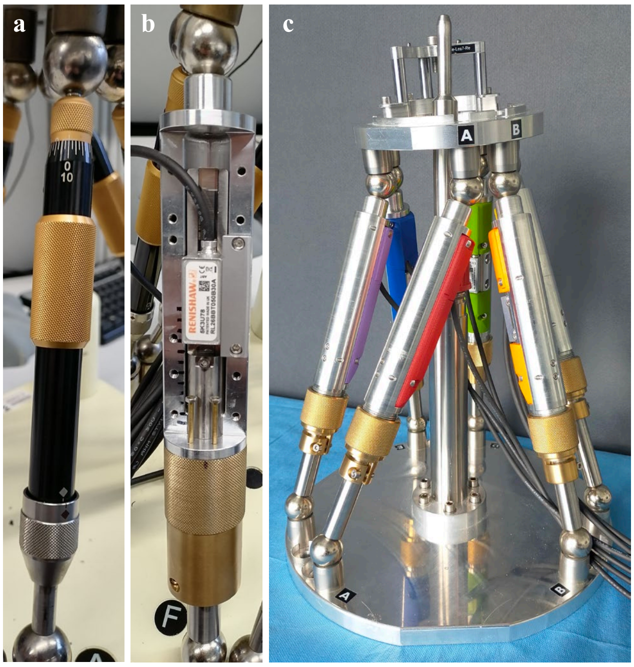

Figure 1: (a) Former analog strut with micrometer screw. (b) New strut with optical length encoder. (c) Whole digitalized alignment device (hexapod) for individual jig customization.

II. Material and methods

Each of the six prismatic joints was equipped with an optical absolute linear encoder (RESOLUTE, RL26BBT050B30A, Renishaw GmbH, Pliezhausen, Germany) that provides continuous, unambiguous readouts of the actual strut length. The sensor offers a resolution of up to 50 nm and communicates via the BiSS-C (Bidirectional Serial Synchronous) protocol. An Arduino

Due together with six RS485-TTL interface modules (one for each strut) were used to receive and manage data communication. The RS458 modules handled the conversion of the differential BiSS signals, allowing the microcontroller to selectively read out the encoder values from each sensor.

An application was developed in MATLAB (R2024a) to integrate all processing steps, including (i) import of patient-specific trajectory data, (ii) computation of the inverse kinematics to receive required strut lengths, (iii) connecting the Arduino to the MATLAB application to obtain live sensor readings, and (iv) real-time visualization of deviations between desired and actual strut lengths with a color-coded visual tolerance alert. The corresponding graphical user interface is shown in Figure 2.

Two separate calibration procedures were performed using an optical coordinate measurement machine (CMM, Keyence XM-M1200). First, the offset between the physical minimum length of each strut and the respective encoder value was calibrated as an average of five measurements. The second calibration measured the geometric relations within the hexapod to account for assembly-related inaccuracies in the inverse kinematics.

III. Results and discussion

A first prototype of the adjustable Gough–Stewart platform, now equipped with integrated real-time digital prismatic joint length sensing, was built to reduce operator-dependent errors. The incorporated absolute linear encoders provide a higher measurement accuracy (50 nm) compared to the vernier scale of the micrometer screws, which has increments of 0.05 mm. Additionally, digits on a digital display are easier to read than markings on a micrometer scale, especially for the untrained personnel. Furthermore, mechanical play, for example in the strut threads, does not affect accuracy as it is also captured by the sensors through design. Finally, users can now adjust the struts in real-time based on the deviation to their target length, not the desired absolute length. Digital readout, therefore, eliminates the risk of human miscalculation or digit mix-ups, as seen in the past [4], directly leading to higher accuracy and thus safety.

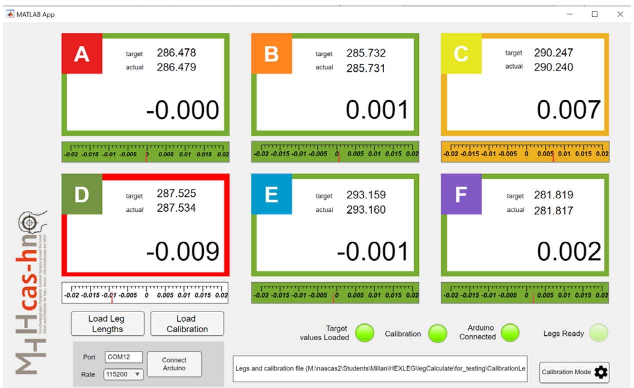

Figure 2: Graphical user interface with color-coded visualization of the deviation between the desire and the actual length of each strut.

In all initial trials, real-time readout of the strut lengths worked reliably, and the color-coded visualization of incorrectly adjusted struts simplified the overall workflow. Digitization also opens opportunities for additional safety features in the future, such as audible alerts or software control that only enables the next step once all six struts meet their target lengths.

In principle, the passive hexapod could be replaced by a motorized and fully automated system. However, such an approach would be significantly more expensive and more complex to maintain. This raises the underlying research question of how much simplicity is feasible and how much technology is truly necessary to ensure a sufficiently high level of patient safety. While reading strut lengths from analog scales is demanding and prone to human errors, adjusting the leg lengths is not a motorically demanding task that can be performed manually with the required accuracy. This makes replacing the manual adjustment with motors unnecessary. Therefore, a digitally enabled passive hexapod offers an effective solution at moderate cost for intraoperative customization of individual drill jigs, balancing accuracy, safety, and ease of maintenance while avoiding the complexity of motors, controllers, and sophisticated automation software.

The principle can also be applied to other non-clinical applications where precise and static positioning is only occasionally required. However, when frequent changes in settings or even dynamic movement of the end-effector platform are necessary, digitizing manually adjustable struts is not a viable alternative.

IV. Conclusions

Integrating digital length sensing into a passive hexapod improves the reliability and accuracy of intraoperative customization without the high cost and complexity of motorization. The approach retains a short, OR–compatible workflow while mitigating human-factor errors associated with reading micrometer values on a vernier scale. Future work will focus on systematically evaluating the accuracy of the digitally enhanced hexapod and comparing it to the previous manual system.

Author's statement

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