Design of a Cost-effective 6DOF Mechanical Armature for Real-Time MRI Scan Plane Prescription

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Introduction: Current real time MRI scan plane prescriptions are typically performed using some form of software user-interface or dedicated hardware input device such as a Spaceball [1]. Using software interfaces, it is generally non-intuitive and time consuming to prescribe a double oblique image plane. It is not intuitive to push, pull, or twist the sphere of a Spaceball to translate and/or rotate the scan plane either. In addition, neither of these interfaces, nor their combination, can provide proper spatial references. There exists no well-established input device for general 3D tasks which may arise in computer graphics and virtual reality [2]. The goal of the research described here is to design and develop a hardware device that is suitable for real time MRI scan plane prescription.

Design Criteria: The identified important factors are: (1) 6-degree-of-freedom (6DOF): The device shall simultaneously provide x, y, z for scan plane positioning and pitch, yaw, roll for its orientation. (2) Bi-directional: It can be used as an input device to prescribe the scan plane as well as an output device to physically reflect the position and orientation of the current scan plane relative to an absolute reference coordinate system. (3) Static balance: the device shall maintain its position and orientation without collapsing to a null rest state when hand support is not available. (4) Visible reference coordinate system such that the geometric information it provides can be easily and intuitively comprehended or appreciated. (5) Cost-effective: approximately the same cost as or cheaper than a personal computer.

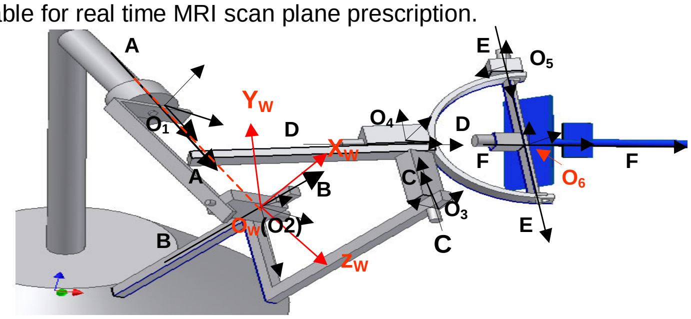

FIG. 1 illustrates the arrangement of the rotational axes and the local coordinate systems, subscripts w and i (i=1, 2, …6) indicate fixed world and local coordinate systems respectively.

Design: A 6-rotational-joint mechanical armature was designed to satisfy the above-identified criteria (Fig. 1). It has a spherical workspace of radius $R=2^*|O_2O_3|=2^*|O_3O_6|$, centered at O_2 (the same as O_w). The combined effects of rotating along the A-A, B-B and C-C axes determines the center position O_6 of the proxy of the scan plane (the blue plane in Fig. 1, later referred to as the proxy). The addition of rotating along the D-D, E-E and F-F axes determines the proxy orientation. The decoupling of positioning from orientation is realized by setting the cross-point of the axes D-D, E-E and F-F to be the center (O_6) of the proxy. At each joint an optical encoder is coupled with a motor. For use as an input device for MRI scan-plane prescription, the encoder readings are used to calculate the position and orientation of the proxy using forward kinematics. For use as an output device the translation vector and rotation matrix of a given prescription is converted to the appropriate joint angles using inverse kinematics. These joint angles are then sent to the motors to automatically translate and rotate the proxy to physically reflect the scan plane.

Implementation: A proof-of-concept device was constructed using aluminum alloy, optical encoders E4 from US Digital and custom modified Hitch servos from Tower Hobby. Static balance was realized by symmetric design, light weight materials, friction, holding torque of motors and, where applicable, counter-weight blocks. The radius of the spherical work space is 220mm, which allows a 1:1 ratio between the armature and MR scanner dimensions for real-time cardiac imaging. The user can hold the stylus (attached to the proxy and serving as its normal) to move the proxy around and simultaneously change its position and/or orientation to prescribe a scan plane. When the scan plane prescription is done through a software user–interface, the proxy can follow the prescribed plane in output mode. In both modes, the proxy can maintain its position and orientation.

Results: Accuracy and precision are used as the performance measures here. A series of target positions/orientations within the spherical workspace were randomly generated. Accuracy is defined as the mean error between the closet proximity to which the armature can actually move and the corresponding random target. Precision is twice the standard deviation of the errors. The positioning accuracy and precision for manual mode are: 0.8mm and 1.3 mm, for automatic mode are 1.8mm and 2.6mm. In automatic mode, the accuracies for orientation (α, β, γ) are: 1.5, 0.6, 0.6 degrees respectively; corresponding precisions are 2.6, 1.0, 1.5 degrees. These performances can be improved by machining with tighter tolerances, reducing inertia by improved static balancing, and using better sensors and motors. There is a cylindrical dead zone along the O_wZ_w axis with radius of 43mm due to mechanical occlusion. The current updating frequency for input mode is 100 Hz and for output mode is 50 Hz. The device works in both Windows and Linux operating systems.

Application Examples: The prototyped 6DOF armature is registered with a patient such that negative Z_w corresponds to the S/I direction, X_w to L/R and Y_w to A/P. A cardiologist can hold the stylus and move it to rapidly prescribe short axis views, long axis views, etc., using the input mode. For coronary artery imaging, one may use a software interface to localize the coronary artery, with the device acting in output mode to indicate where you are. Then using the device in its input mode, fine adjustments of the scan plane can be made for small variations associated with different breathholds.

Conclusion: A cost-effective 6DOF mechanical armature was designed and prototyped to intuitively and efficiently prescribe real-time MRI scan planes. Future work will produce a stronger device with better mechanical quality. Human performance experiments will be conducted to test its usefulness in real-time MRI applications.

References: [1] Christopher J. Hardy et al. (1998) Interactive Coronary MRI. MRM 40:105-111. [2] Shumin Zhai (1998) User Performance in Relation to 3D Input Device Design, Computer Graphics 32(4). Pp50 – 54.