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Placement of accelerometers for high sensing resolution in micromanipulation

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ABSTRACT

High sensing resolution is required in sensing of surgical instrument motion in micromanipulation tasks. Accelerometers can be employed to sense physiological motion of the instrument during micromanipulation. Various configurations of accelerometer placement had been introduced in the past to sense motion of a rigid-body such as a surgical instrument. Placement (location and orientation) of accelerometers fixed in the instrument plays a significant role in achieving high sensing resolution. However, there is no literature or work on the effect of placement of accelerometers on sensing resolution. In this paper, an approach of placement of accelerometers within an available space to obtain highest possible sensing resolution in sensing of rigid-body motion in micromanipulation tasks is proposed. Superiority of the proposed placement approach is shown in sensing of a microsurgical instrument angular motion by comparing sensing resolutions achieved as a result of employing the configuration following the proposed approach and the existing configurations. Apart from achieving high sensing resolution, and design simplicity, the proposed placement approach also provides flexibility in placing accelerometers; hence it is especially useful in applications with limited available space to mount accelerometers.

1. Introduction

To improve micromanipulation accuracy of surgeons, a number of engineered devices or systems have been or are being developed. These include telerobotics systems [1–3], steady-hand robotics systems [4], and hand-held active tremor compensation instruments [5–8] which have been under research and development for a few years. The instruments have three main parts: sensing, filtering or processing of sensed data, and manipulation. Accurate sensing of the tremor motion of the surgical tool attached to the distal end of the instrument is important for effective compensation for the tremor [9,10].

In the instruments described in [6–8], motion of the surgical tool is calculated by rigid-body kinematics using micromachined inertial sensors. Inertial sensors are employed because they do not have line-of-sight problem which exists in other sensing modalities such as optical-based sensing and ultrasonic-based sensing. Micromachined type inertial sensors are chosen due to their compactness in size, light in weight, and cheapness. In earlier instrument prototypes [6,7], micromachined accelerometers and gyroscopes are used for sensing three degrees-of-freedom (DOF) translational motion and three DOF angular motion, respectively. In the successive instrument [8,11], only accelerometers are employed since it is found out that angular sensing resolution provided by micromachined gyros is poorer than that derived from micromachined accelerometers for a given space inside the instrument [11,12]. However, it is stated in [8] that sensing resolution of the hand-held instrument is still poor to have effective compensation. This might have resulted from non-optimal placement of accelerometers in the instrument. Therefore, the authors performed literature review on angular motion sensing using only accelerometers to find accelerometer placement which provides better sensing resolution.

The concept of the viability of the use of linear accelerometers to measure angular motion of a rigid body is introduced in 1965 [13]. A number of researchers contribute towards the improvement of the original concept [14,15]. There seem to be little progress in this area of rigid body motion detection using accelerometers from 1979 until 1994 when an original cube configuration of placement of six accelerometers, the minimum number of accelerometers required to detect six degrees-of-freedom (DOF) motion of a rigid body [16], is introduced by Chen et al. [17]. Several researchers have been working on the improvement of gyro-scope free inertial navigation systems (GF-INS) based on the original cube configuration [18–22]. However, there is little or no literature or research on the effect of accelerometer placement on motion sensing resolution/precision.

The use of the cube configuration is neither feasible nor yields highest possible sensing resolution in some applications such as

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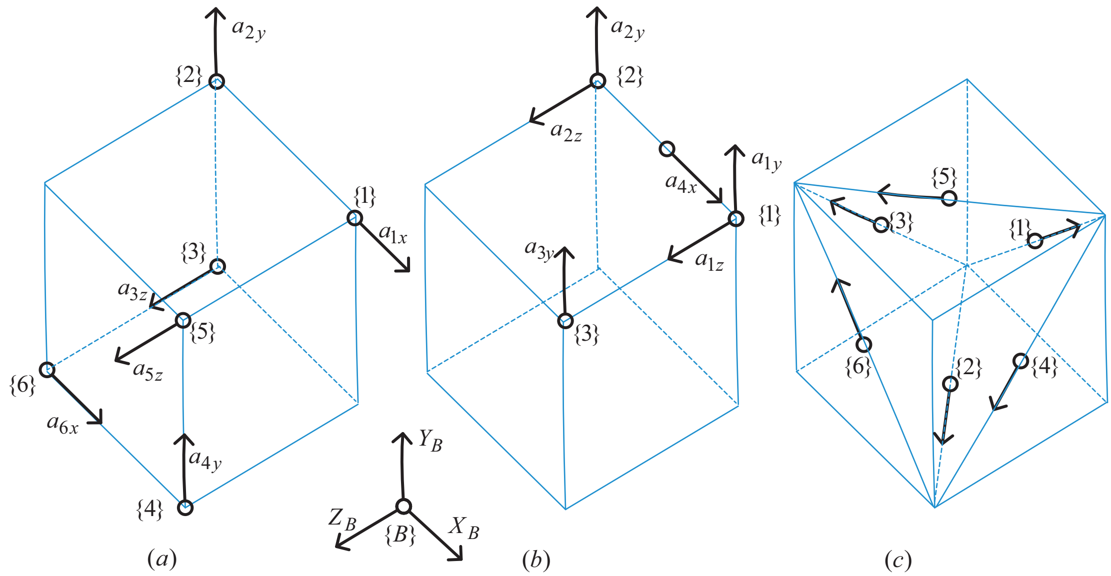

Fig. 1. Three different configurations of accelerometer placement within the same space available to detect six DOF motion.

tremor compensation owing to space constraints: the space available is not in cube shape. In these situations, researchers have to seek for other accelerometer placement configurations within the given space constraints [8,11,23]. The configurations are not optimal in terms of resolution. There are no guidelines or rules from the view point of precision for the general placement configuration of accelerometers to detect six DOF motion of a rigid body. For example, for a given same space available, three different accelerometer placement configurations involving six accelerometers to detect six DOF motion are shown in Fig. 1. All the three placement configurations can provide six DOF motion sensing. The configuration on the right is the cube configuration introduced by Chen et al. [17]. However, it is not obvious which one would provide the highest angular sensing resolution.

Therefore, it is necessary to find out and propose accelerometer placement configurations to yield high sensing resolution without having to restrict the design to the cube configuration, thereby allowing the highest possible sensing resolution for a given space constraint.

2. Placement of accelerometers

In this section, propositions for placement of a pair of two accelerometers to detect an angular acceleration component (one DOF angular acceleration) with the highest possible angular acceleration resolution (i.e., the lowest possible angular acceleration sensing noise) in micromanipulation tasks, and proofs of the propositions are described. To detect all the three angular acceleration components, two more pairs of accelerometers can simply be employed. To reduce the number of accelerometers required to a minimum, sensing of the other two components (two DOF angular acceleration) only with three accelerometers is described. To minimize sensing noise of these two components, constrained optimization using the space constraints is proposed. Placement configurations for sensing three DOF angular motion, and six DOF motion are then presented.

2.1. Propositions for one DOF angular acceleration

Only a pair of two accelerometers is required by the proposed placement to sense a particular angular acceleration component. The two accelerometers must be placed so that their sensing directions are the same (i.e., their sensing axes are parallel to each other). The propositions are as follows.

Proposition (i). Separation distance along a principal axis (i.e., perpendicular distance) between the two sensing axes of the accelerometers must be as large as possible (d_1 in Fig. 2 represents the separation distance). A square box is added in the figures for better visualization of placement of accelerometers, and representation of space available.

Proposition (ii). The two accelerometers must be placed in a way that their sensing axes form a plane perpendicular to the principal axis about which the angular acceleration is calculated. The line which passes the two accelerometers should be perpendicular to the sensing axes to keep the negligible error minimum. Even if it is not perpendicular, the added error can still be negligible. The accelerometers shown in Fig. 2(b) form a perpendicular plane, but the line passing through them is not perpendicular to their sensing axes. The accelerometers shown in Fig. 2(c) do not form a perpendicular plane and hence the placement does not satisfy the proposition (ii) (d_2 in Fig. 2 represents an offset distance which prevents the accelerometer axes from forming a perpendicular plane).

The placement that does not satisfy (ii) will require knowledge of another angular acceleration component in the calculation of a particular angular acceleration component resulting in more noise in the angular acceleration, or requiring more accelerometers. The amount of extra noise is dependent on the amount of the offset.

2.1.1. Proof of propositions

The total accelerations, A_i, each accelerometer at $\{i\}$ senses include the inertial acceleration of the body, A_{IN}, the gravity, G, and the rotation-induced accelerations: the centripetal acceleration, $A_{i/C}$, and the tangential acceleration, $A_{i/T}$:

$$A_i = A_{IN} + G + A_{i/C} + A_{i/T}, i = 1, 2; \tag{1}$$

$$A_i = A_{IN} + G + \underbrace{\Omega \times (\Omega \times R) + \alpha \times R}_{\text{Rotation-induced accelerations}} \tag{2}$$

where all the variables are relative to the body frame $\{B\}$, $\Omega = [\,\omega_x \quad \omega_y \quad \omega_z\,]^T$ is the angular velocity vector, R is the vector from the unknown instantaneous center of rotation to the point of sens-