IMU-based Manipulator Kinematic Identification

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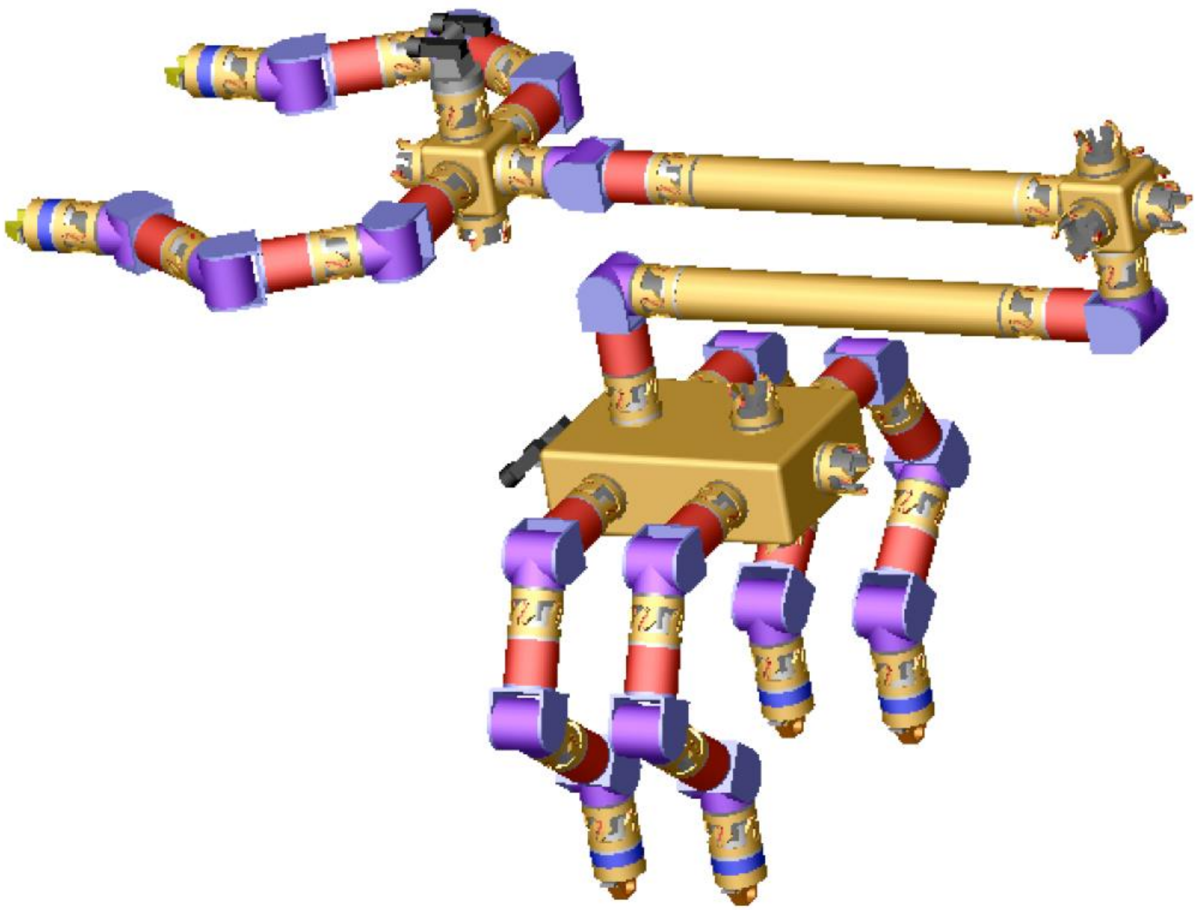
Background and Motivation

Reconfigurable robots are useful for maximizing the utility of a system as environmental and mission parameters evolve

- Modularity promotes easy removal/replacement of failed parts
- Adjustable kinematics enables accommodation of a wide variety of tasks and operational requirements

But every time the system is reconfigured, a new kinematics model must be generated if the task is to be performed in a Cartesian task space

→ Being able to do so quickly and with minimal human intervention helps minimize the cost of reconfiguration and thus improves overall system utility across a variety of tasks



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Prior Work: Kinematic Identification

Some prior work (See, e.g., [1] and [2]) depends on an established kit of parts having known parameters, but constraining the system to a pre-established kit in this fashion limits reconfiguration options

Existing other techniques [3], [4], [5], [6], [7], [8] typically require either measurement or implicit knowledge of the end effector position, which can be difficult to obtain in non-laboratory settings

The use of an IMU, in the manner of Canepa et al. [9], enables a self-contained kinematics detection system in a manner nearly independent of the operating environment

- This technique relies on the presence of gravity, and performs a numerical integration that may increase susceptibility to accumulation of error due to sensor noise

The goal of the present work is to develop a kinematic identification scheme that is applicable both on planetary surfaces and in microgravity

Specifically:

-What is the minimum possible scheme employing one or more IMUs?

-How can we use sensor data directly, without numerical integration?

Background: Screw Description of Kinematics

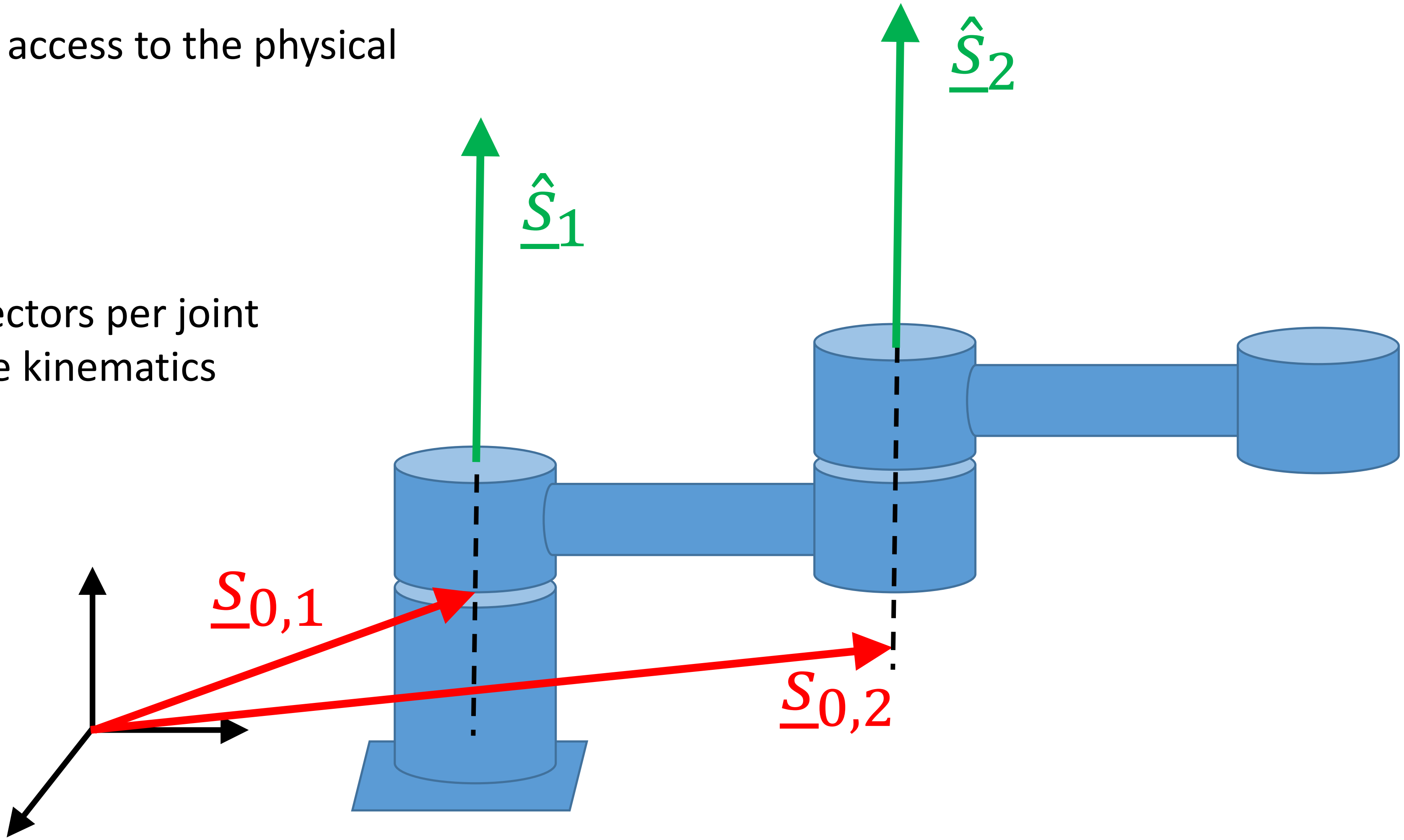
Denavit-Hartenberg parameters do not readily lend themselves to direct use in the present context.

- "Zero" pose dictated by arbitrary convention

Screw description allows direct access to the physical parameters of relevance:

- Screw axis location $\underline{\hat{s}}_i$
- Screw axis direction $\underline{s}_{0,i}$

And knowledge of these two vectors per joint is sufficient to fully describe the kinematics



Kinematic Equations of Motion

Suppose we move a single joint with angular rate $\underline{\omega}$ and angular acceleration $\underline{\alpha}$

The screw axis direction can be readily identified from a rate gyro reading

$$\underline{\hat{s}}_i = \frac{\underline{\omega}}{\|\underline{\omega}\|}$$

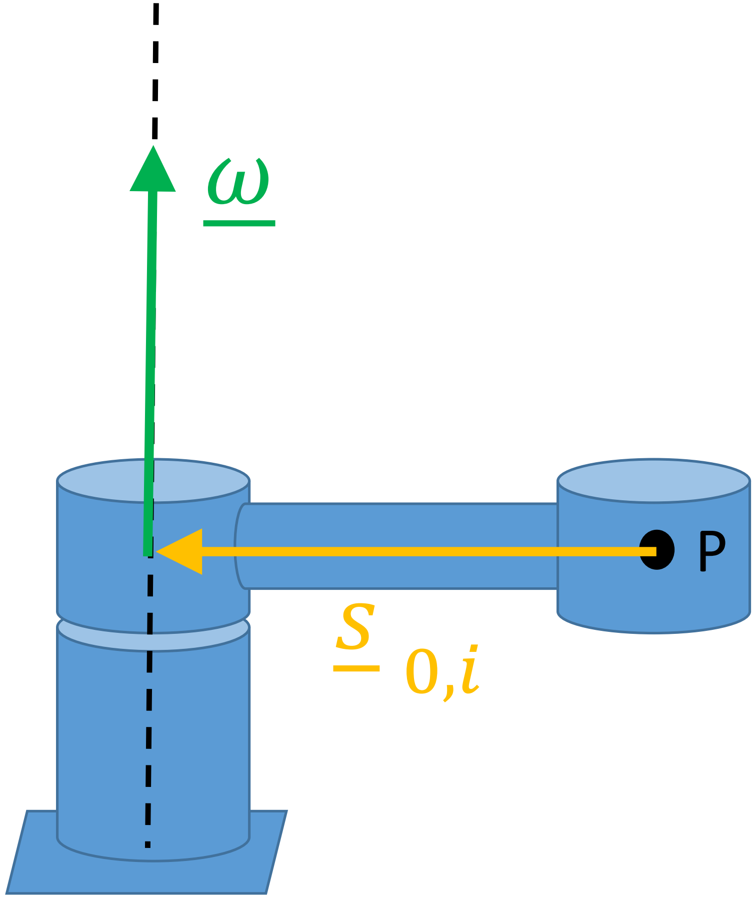
An IMU at point P will experience translational acceleration

$$\underline{a} = \underline{\alpha} \times \underline{s}_{0,i} + \underline{\omega} \times \underline{\omega} \times \underline{s}_{0,i}$$

This is a linear function of screw axis location

$$\underline{a} = [\underline{\alpha}^{\times} + \underline{\omega}^{\times}\underline{\omega}^{\times}]\underline{s}_{0,i} = \mathbf{M}\underline{s}_{0,i}$$

If gravity is present, the accelerometer will differ from $\underline{a}$ by the local acceleration due to gravity. This can be identified via low-speed traversal of the trajectory, and subtracted from the IMU reading.



Caveat: Solving the linear system

The screw axis location enters our linear system of equations only by way of cross products:

$$\underline{a} = [\underline{\alpha}^\times + \underline{\omega}^\times \underline{\omega}^\times]\underline{s}_{0,i} = \mathbf{M}\underline{s}_{0,i}$$

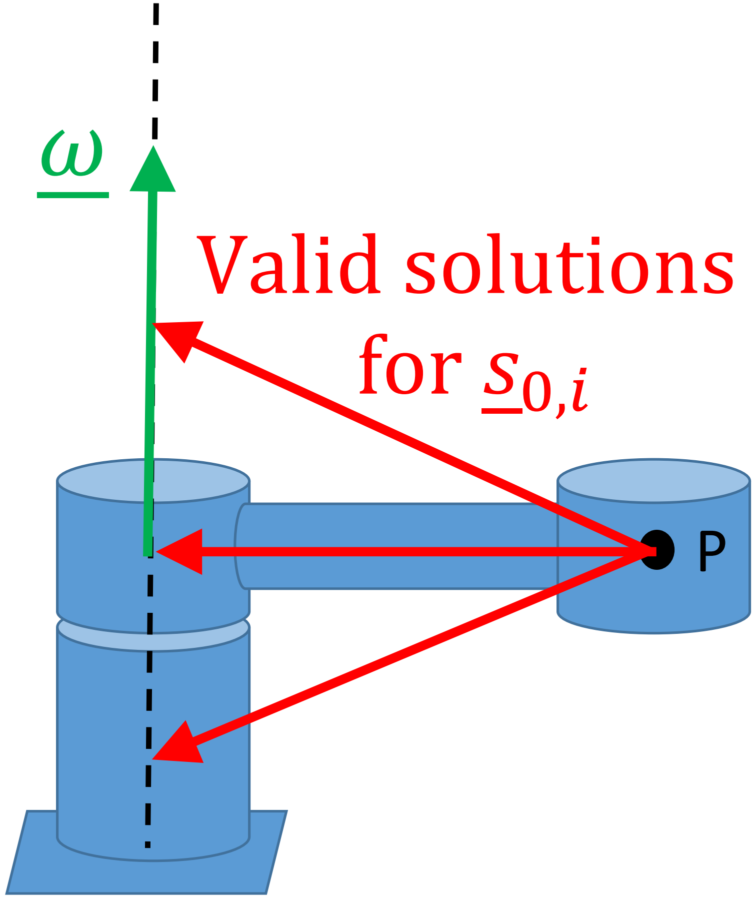
This matrix **M** will therefore *always* be singular. The problem, however, is one of non-*uniqueness* (never non-*existence*) of the solution

Any valid solution will yield an equivalent forward kinematics model

A truncated singular value decomposition can be used to identify such a solution

- Decompose **M** = **UΣV**^{T}
- Discard zero singular value in computing solution $$\underline{s}_{0,i} = \sum_{\substack{j=1 \\ \sigma_j \neq 0}}^{3} \frac{\underline{u}_j^T \underline{a}}{\sigma_j} \underline{v}_j$$

(where u_j and v_j are the columns of **U** and **V**, respectively; and σ_j are the diagonal values of **Σ**)



Identification Algorithm

For each joint (i = 1, …, N):

1. Execute a back-and-forth (e.g., sinusoidal) motion
   - If gravity is present, do this at both low and high speeds so gravity can be subtracted
2. Identify associated screw axis direction from resulting angular velocity

$$\hat{\underline{s}}_i = \frac{\underline{\omega}}{\|\underline{\omega}\|}$$

3. Identify screw axis location by solving the linear system (where $\underline{a}$ is corrected for gravity from step 1)

$$\underline{a} = \left[\underline{\alpha}^{\times} + \underline{\omega}^{\times}\underline{\omega}^{\times}\right]\underline{s}_{0,i} = \mathbf{M}\underline{s}_{0,i}$$

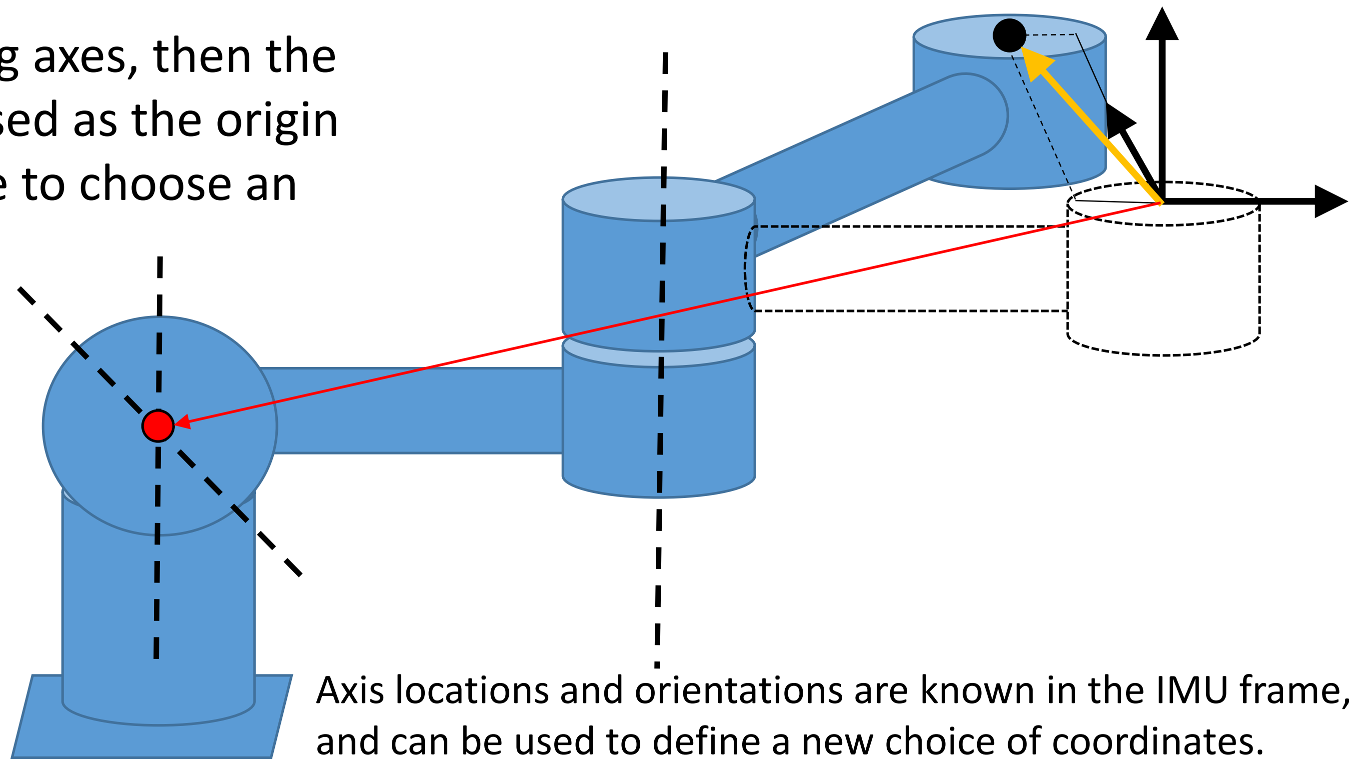
In principle all of this can be done with a single instantaneous measurement for each joint; but noise will be substantial and averaging the results of many measurements is advised.

Caveat: Coordinate frame

Since we're doing all of this in the IMU coordinate frame, our kinematics model will give us position with respect to the IMU location in the reference pose

Mathematically, there's nothing wrong with this; but we probably would prefer to convert this into a coordinate frame attached to the base of the manipulator (since this part would generally be fixed to the environment in a known way)

If a shoulder module is used having to intersecting axes, then the intersection point can be readily identified and used as the origin of the coordinate system; and the end user is free to choose an appropriate convention for axis orientation (e.g., shoulder positive pitch = x axis, and shoulder positive roll = z axis)



Axis locations and orientations are known in the IMU frame, and can be used to define a new choice of coordinates.

Experimental Setup

Ciarleglio [11] implemented this for evaluation on the Ranger Mark I manipulator

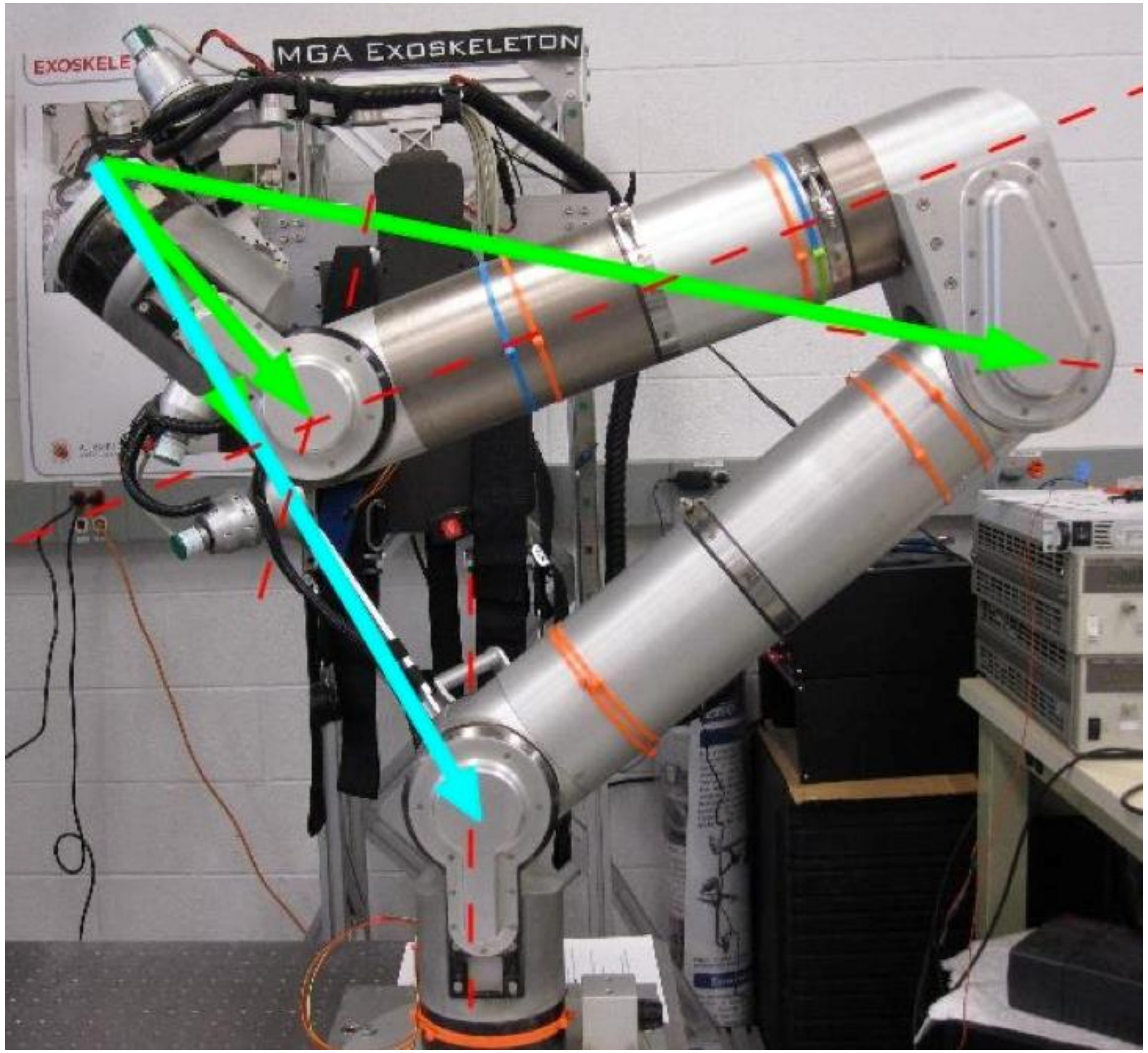
6DOF manipulator with identification attempted for joints 2, 3, 4, and 5.

Trajectory nominally swept 10° of arc

- Period of 0.36 sec for Joints 4 and 5 (4 cycles per joint)
- Period of 1.0 sec for Joints 2 and 3 (6 cycles per joint)

Memsense Nano IMU placed at tip

A moving average filter was applied to all data; and angular rate readings were projected on to the best-fit axis to further reduce the effect of noise.



Experimental Results

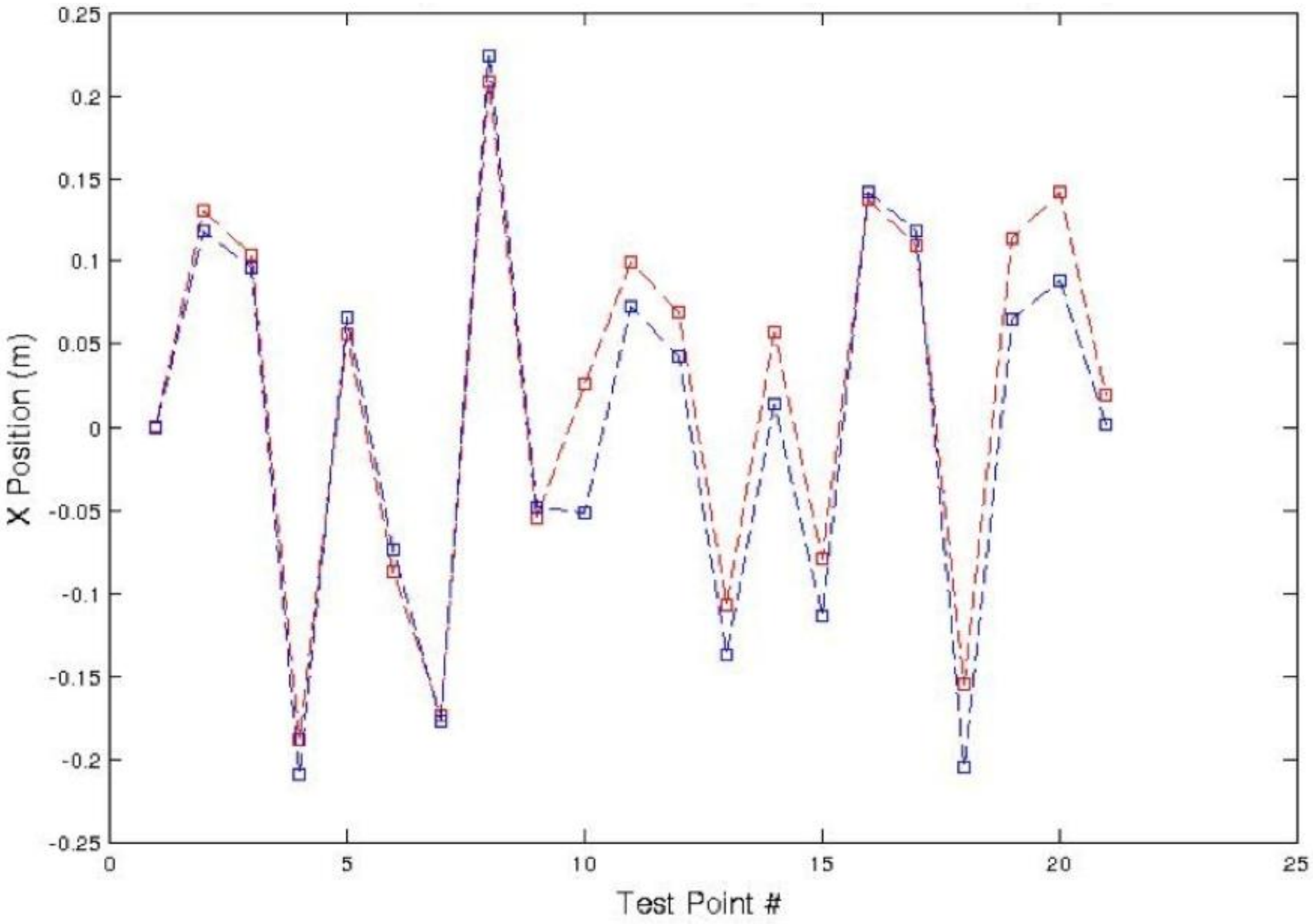
IMU measurement noise was on the order of 40-90% of the measured value.

Resulting screw axis locations differed by approximately 11% on average versus measurements taken by hand

Screw axis directions were correct to visual inspection

Resulting kinematic model was compared against known trusted model for a sampling of 21 different poses within the workspace

- Discrepancies averaging 17% for magnitude delta from original (calibration) pose



Discussion and Conclusions

A simple, analytically-based technique has been presented for the identification of a completely unknown kinematic chain on the basis of IMU readings from the tip

Experimental results suggest that sensor noise is a significant impediment to the practical utility of this scheme

- If an accurate CAD model is available, then this certainly couldn't compete
- If the kinematic model is truly unknown (e.g., due to damage to or improvisation of structural components), then this might be worthwhile

Possible avenues for improvement of experimental setup:

- Canepa et al. [9] used a mechanical mount to increase the moment arm to the IMU
- More motion cycles would provide more data for mitigating zero-mean noise
- A more sensitive IMU might improve performance (provided sensitivity to electrical noise does not become an issue)

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