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Abstract
Providing adequate operational information to the International Space Station (ISS) robotics operators for overall arm configuration is critical for the operators’ situational awareness in performing robotics tasks, especially when visual cues are limited. In this study, the Canadian Space Station Remote Manipulator System (SSRMS) is used as a demonstration model representing ISS robotics, and three evaluation indices for arm configuration in manual mode operation are proposed and examined in an example robotics operation. These indices will increase the operator’s situational awareness in overall arm configuration, especially for monitoring the clearance of the arm with respect to the surrounding structures.

1 INTRODUCTION
The SSRMS[1][2][3] has been in operation since 2001 aboard the ISS and plays a key role in the assembly and maintenance of the ISS. The Canadian Special Purpose Dexterous Manipulator System (SPDM), the Japanese Experiment Module Remote Manipulator System (JEMRMS) Main Arm (MA) and Small Fine Arm (SFA), and the European Robotic Arm (ERA) will join the ISS in the near future. SSRMS, SPDM, and ERA each consist of 7 joints, while JEMRMS MA and SFA each consist of 6 joints.

The extensive operational experience of the Space Shuttle’s Remote Manipulator System (SRMS), which has 6 joints, played a significant role in the design and operation of the ISS robotics. However, optimization of the ISS robotics operation for different types of tasks utilizing the unique redundancy characteristics of the 7-joint systems is still underway. Although consistently monitoring the overall arm configuration and the clearance between the robotic arm and the surrounding ISS structure is essential for safe robotics operation, it is frequently a challenging task for the robotics operators due to the limited camera views for robotics operation on the ISS.
2. MANUAL MODE OPERATION OF THE SSRMS

Manual mode operation of ISS robotics is defined as a human-in-the-loop control mode of the arm’s Frame of Resolution (FOR) using the Rotational Hand Controller (RHC) and the Translational Hand Controller (THC). The FOR data, which are the position and attitude data of a reference point, joint angles, as well as information concerning the seven-joint singularities, are available at the Robotics Work Station (RWS), which is the human-machine-interface for SSRMS control on board the ISS. Overall arm geometry is monitored via TV camera views without a direct view. A gross pitch plane motion of the arm cannot be intuitively recognized by the operator with only the FOR or joint angle telemetries, and visual monitoring of the arm is crucial in monitoring the clearance from the surrounding structure.

2.1 Arm Kinematics

The SSRMS has 7 joints and the degree of freedom of each joint from the base to the tip is Roll-Yaw-Pitch-Pitch-Pitch-Yaw-Roll.

The joint angles are defined as follows;
$$\theta_{SR}, \theta_{SY}, \theta_{SP}, \theta_{EP}, \theta_{WP}, \theta_{WT}, \theta_{WR}$$

The frame $Ai$ is a base coordinate system fixed to each link and is expressed by
$$\{a^i\}, \ (i=0,1,...,6,7)$$

Each link vector is expressed by
$$r_i = \{a^i\}^T r_i, \ (i=0,1,...,6,7)$$

The directional cosine matrix $C_{Ai+1/i}$ from the Ai to Ai+1 system is expressed by
$$C_{Ai+1/i}$$

The location of the FOR of the arm is expressed by
$$\mathbf{R}_v = r_0 + r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 \quad (1)$$

2.2 Arm Control Mode

The manual mode operation of the demonstration model of the SSRMS for this study is performed in three different ways:

1) All joints are movable with inverse kinematics so that the sum of the squares of each joint’s motion is minimized.

2) Either the Shoulder Roll (SR) or Shoulder Yaw (SY) joint is held, that is, a zero rate is commanded to the SR/SY joint as long as the arm is outside of the six-joint singularity regions, and the SR or SY joint is released and moves when approaching a six-joint singularity.

3) Either the SR or SY joint is locked, that is, a zero rate is constantly commanded to the SR or SY joint.

3. EVALUATION INDICES FOR ARM CONFIGURATION

The following three evaluation indices are introduced for overall arm configuration monitoring.

1) Manipulability Index : $w$

The Manipulability Index $w$, proposed by Yoshikawa[4], can be considered as an index to show a conceptual distance from a singularity point and is used in order to identify the arm’s singularity conditions. The three kinds of manipulability indices, which correspond to the arm control mode as shown in Section 2.2, are defined as follows:
Manipulability Index \( w \) with seven joints movable

\[
X = J \begin{bmatrix} \dot{\theta}_{SR} & \dot{\theta}_{SY} & \dot{\theta}_{SP} & \dot{\theta}_{EP} & \dot{\theta}_{WP} & \dot{\theta}_{WY} & \dot{\theta}_{WR} \end{bmatrix}^T
\]
\[
w = \sqrt{\det(JJ^T)}
\] (2)

Manipulability Index \( w_{\text{Roll}} \) with six joints movable (SR joint fixed)

\[
X = J_{\text{Roll}} \begin{bmatrix} \dot{\theta}_{SY} & \dot{\theta}_{SP} & \dot{\theta}_{EP} & \dot{\theta}_{WP} & \dot{\theta}_{WY} & \dot{\theta}_{WR} \end{bmatrix}^T
\]
\[
w_{\text{Roll}} = |\det(J_{\text{Roll}})|
\] (3)

Manipulability Index \( w_{\text{Yaw}} \) with six joints movable (SY joint fixed)

\[
X = J_{\text{Yaw}} \begin{bmatrix} \dot{\theta}_{SR} & \dot{\theta}_{SP} & \dot{\theta}_{EP} & \dot{\theta}_{WP} & \dot{\theta}_{WY} & \dot{\theta}_{WR} \end{bmatrix}^T
\]
\[
w_{\text{Yaw}} = |\det(J_{\text{Yaw}})|
\] (4)

2) Elbow Motion Index: \( EW \)

Monitoring the motion of the elbow area is critical to avoid a collision of the arm with the surrounding structures. The index \( EW \) is now defined as the ratio of the norm of an infinitesimal displacement vector of the wrist to the norm of an infinitesimal displacement vector of the elbow and is used to evaluate the displacement of the elbow area when the arm tip is maneuvered.

\[
EW = \frac{\|\delta R_{\text{elbow}}\|}{\|\delta R_{\text{wrist}}\|}
\] (5)

\( R_{\text{elbow}} \) and \( R_{\text{wrist}} \) are the positions of the elbow and wrist, respectively, with respect to the arm base coordinate system, A0, as shown in Figure 2.

3) Pitch Triangle Plane (PTP) Change Index: \( \omega_p \)

Pitch plane change should also be closely monitored in order to avoid a collision of the arm with the surrounding structures. A pitch plane change is equivalent to the rotation of the Pitch Triangle Plane (PTP) about the roll and/or yaw axis in the P coordinates system (See Figure 2).

The directional cosine matrix \( C^{P/A0} \) from the A0 to the P coordinate system is expressed as

\[
C^{P/A} = C_z(\phi)C_y(\theta_{SY})C_y(\theta_{SR})
\] (6)

where

\[
\phi = \theta_{SP} + \frac{1}{2} \theta_{EP}
\] (7)

\( \phi \) is the PTP pitch angle with respect to the base coordinate system. If the angular rate vector of the P coordinate system \( \omega_p \) is defined as

\[
\omega_p = \omega_{P/A0} = [p]^T \begin{bmatrix} \omega_{p1} \\ \omega_{p2} \\ \omega_{p3} \end{bmatrix}
\] (8)

Then, \( \omega_p \) can be reduced to

\[
\omega_p = \begin{bmatrix} 0 \\ \phi \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \theta_{SR} \end{bmatrix} + \begin{bmatrix} 0 \\ \theta_{SY} \end{bmatrix}
\]

\[
= \begin{bmatrix} \cos \phi \cos \theta_{SY} & -\sin \phi & 0 \\ -\sin \theta_{SY} & 0 & 1 \\ \sin \phi \cos \theta_{SY} & \cos \phi & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_{SR} \\ \dot{\theta}_{SY} \\ \dot{\phi} \end{bmatrix}
\] (9)

Let us focus on the PTP motion characteristics in the rotation about the roll axis of the PTP since it is the most critical motion of the PTP in monitoring the clearance with respect to the surrounding structure.
during arm operation. In the operation cases where all 7 joints are movable, generic arm motion characteristics cannot be obtained due to non-unique inverse kinematics. In SR-held case and SY-held case, where the remaining 6 joints are movable, the motion characteristics in the rotation about the roll axis of the PTP are obtained from Equation (9). In the SR-held case,

$$\omega_{P_{roll}} = -\sin \phi \cdot \dot{\theta}_{SY}$$

(10)

Thus, the coefficient reaches a maximum, resulting in a large PTP rotation rate about the roll axis of the P system when

$$\phi = \pm \frac{\pi}{2}$$

Similarly, in the SY-held case,

$$\omega_{P_{roll}} = \cos \phi \cos \theta_{SY} \cdot \dot{\theta}_{SR}$$

(11)

Thus, a large PTP rotation about the roll axis of the P system occurs when

$$\phi = 0, \pm \pi \quad \text{and} \quad \theta_{SY} = 0, \pm \pi$$

Therefore, the PTP pitch angle \(\phi\), defined in Equation (7), and \(\theta_{SY}\) are significant parameters that indicate a change in the overall arm configuration as well as singularities.

Furthermore, in order to evaluate the PTP motion, the angular rate vector of the P system, \(\omega_P\), in Equation (9) is broken down into increments.

$$\omega(i) = \begin{bmatrix} \cos \phi(i) \cos \theta_{SY}(i) & -\sin \phi(i) & 0 \\ -\sin \phi(i) \cos \theta_{SY}(i) & \cos \phi(i) & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \theta_{SR}(i) - \theta_{SR}(i-1) \\ \theta_{SY}(i) - \theta_{SY}(i-1) \\ \phi(i) - \phi(i-1) \end{bmatrix}$$

(12)

The indices \(EW\) and \(\omega_P\) are both newly introduced indices. While the index \(EW\) indicates overall arm configuration change by evaluating the motion of the arm’s elbow area, which is critical in monitoring the clearance of the arm with respect to the surrounding structure, the index \(\omega_P\) indicates a more detailed overall arm configuration change by evaluating the change rate of the PTP orientation.

4. EVALUATION OF ARM OPERATION WITH THE PROPOSED INDICES

The arm operation path shown in Figure 3 and Table 1 was used as an example to apply the evaluation indices described in Section 3. The initial arm control method was SY-held. Between Position (Pos) 3 and Pos 4, the condition where all joints are movable occurred due to a 6-joint singularity with SY-held. Manipulability and PTP motion were examined using an example trajectory. In order to evaluate the example arm path from a macroscopic viewpoint, the computational results of the values of the three Manipulability Indices \(w, w_{Roll}, \) and \(w_{Yaw}\), using \(\phi\) and \(\theta_{SY}\) as parameters, are shown in Figure 4 with the superimposed values of Pos 1 and 5. Figure 5 shows the computational results of the PTP rotation rate about the roll and yaw axes of the P system, using Equation (9) for SR-held and SY-held cases. Table 2 and Figure 4 indicate that \(w_{Yaw}\) in the SY-held case is larger than \(w_{Roll}\) in the SR-held case at Pos 1, while \(w_{Roll}\) in the SR-held case is larger than \(w_{Yaw}\) in the SY-held case at Pos 5. Table 3 shows that the \(EW\) between Pos 1 and 2 is fairly large compared with those between Pos 2 and 3 and between Pos 3 and 4. This is because a large PTP rotation in roll occurred without significant translation of the FOR. However, the PTP rotation became smaller in the path of Pos 2 to 3 to 4 after enabling the previously held SY joint at Pos 2, resulting in a smaller \(EW\) in this path. Figure 5 shows that, at Pos 1, the PTP rotation in roll and the \(EW\) value are smaller in the SY-held than in the SR-held case, while the PTP rotation in yaw is larger in
the SY-held than in the SR-held case. On the other hand, between Pos 2 and 5 in the SY-held case, $EW$ is relatively large, indicating that a large PTP rotation in roll could occur. Therefore, in the case of a large $EW$, the robotics operator may feel a larger change of overall arm configuration compared to the expected FOR motion.

Currently, the primary operator’s cues at RWS for overall arm configuration are TV camera views, FOR data and joint angle data. No designated telemetry data is available at the RWS concerning the elbow motion, which is critical in monitoring clearance. Providing the numerical and graphical data of $EW$ to the operator as well as a graphical predictor of the PTP superimposed on a bird’s-eye-view of the arm configuration data will enhance the operator’s situational awareness in monitoring overall arm configuration and will also allow the further utilization of the unique advantages of 7-joint arms.

Table 1 Example of Arm Motion (unit: deg)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Before SY Release</th>
<th>Before SY Release</th>
<th>At SY Release</th>
<th>During SY Release</th>
<th>After SY Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>-73.3</td>
<td>-140.1</td>
<td>-149.0</td>
<td>-155.8</td>
<td>-160.0</td>
</tr>
<tr>
<td>SY</td>
<td>49.0</td>
<td>49.0</td>
<td>49.0</td>
<td>46.4</td>
<td>42.7</td>
</tr>
<tr>
<td>SP</td>
<td>-39.9</td>
<td>-134.65</td>
<td>-141.52</td>
<td>-144.4</td>
<td>-143.8</td>
</tr>
<tr>
<td>EP</td>
<td>-118.5</td>
<td>-67.0</td>
<td>-65.6</td>
<td>-64.7</td>
<td>-67.0</td>
</tr>
<tr>
<td>WP</td>
<td>-63.4</td>
<td>-128.3</td>
<td>-128.9</td>
<td>-131.8</td>
<td>-133.0</td>
</tr>
<tr>
<td>WY</td>
<td>28.9</td>
<td>-3.4</td>
<td>-0.6</td>
<td>3.27</td>
<td>7.45</td>
</tr>
<tr>
<td>WR</td>
<td>-46.0</td>
<td>-91.1</td>
<td>-83.4</td>
<td>-71.1</td>
<td>-59.6</td>
</tr>
</tbody>
</table>

Table 2 Manipulability

<table>
<thead>
<tr>
<th></th>
<th>Pos 1</th>
<th>Pos 3</th>
<th>Pos 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_1$</td>
<td>228.3392</td>
<td>743.4717</td>
<td>758.0435</td>
</tr>
<tr>
<td>$w_{roll}$</td>
<td>28.5726</td>
<td>514.3815</td>
<td>516.6911</td>
</tr>
<tr>
<td>$w_{yaw}$</td>
<td>150.6031</td>
<td>32.7451</td>
<td>17.1996</td>
</tr>
</tbody>
</table>

Table 3 PTP Motion

<table>
<thead>
<tr>
<th></th>
<th>Pos 2</th>
<th>Pos 3</th>
<th>Pos 4</th>
<th>Pos 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EW$</td>
<td>1.8583</td>
<td>0.7262</td>
<td>0.7416</td>
<td></td>
</tr>
<tr>
<td>$|\delta \mathbf{R}_{arm}|$</td>
<td>0.2140</td>
<td>0.8591</td>
<td>0.9191</td>
<td></td>
</tr>
<tr>
<td>$\omega_p$</td>
<td>-0.0913</td>
<td>-0.0852</td>
<td>-0.0544</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.2132</td>
<td>-0.1294</td>
<td>-0.0575</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.0091</td>
<td>-0.0506</td>
<td>-0.0673</td>
<td></td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

This study has clarified that the ratio of the norm of a wrist displacement vector to the norm of an elbow displacement vector is an essential parameter for a robotics operator in order to detect a change in the arm’s overall configuration. Also noted is that, for the example trajectory, the control method with 7 joints movable is preferred to the SR or SY joint held since the magnitude of manipulability with the SR or SY held method changes extensively during the maneuver, and this change is not intuitive to the operator.

Providing the arm operator with the information related to elbow motion, such as $EW$ and PTP graphical predictor, which indicate the pitch plane change, will increase the operator’s situational awareness in monitoring the clearance of the arm with respect to the surrounding structure and will enhance the operational safety, mission success, and training efficiency of the ISS robotics.
(a) 7 Joints Movable
(b) SR-Fixed 6 Joints Movable
(c) SY-Fixed 6 Joints Movable

Figure 4 Evaluations of Manipulability

(a) Coefficient for $\omega_{roll}$ during SR-fixed
(b) Coefficient for $\omega_{yaw}$ during SR-fixed
(c) Coefficient for $\omega_{roll}$ during SY-fixed
(d) Coefficient for $\omega_{yaw}$ during SY-fixed

Figure 5 PTP Rotation Factors
REFERENCES


