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# An Inquiry into Skeleton Tracking Applications for Space Exploration

*Research Article*

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## Broad Picture

Exploration of space and the aspiration to become an interplanetary species have long been humanity's dream. Engaging in research related to space exploration not only advances our understanding of fundamental sciences but also motives us to innovate new technologies and create industries dedicated to space exploration. It also challenges us to address profound questions about our existence in the vast Universe. Despite these great ambitions, maintaining the health of astronauts and improving the productivity of explorations in space remain formidable challenges in current space programs. The human body, given its biological conditions, is not suitable to endure extreme challenges such as high radiation and low gravity prevalent in space. Consequently, researchers have been actively developing various Human-Robot Interfacing (HRI) systems to enhance both the physical and mental performance of the human body in the demanding environment of space. Until now, HRI in space has predominantly revolved around remote engagement between humans on Earth and robots in space. This interaction has mainly involved teleoperations, ranging from direct control to intermittent supervisory control. Recent NASA efforts, however, have expanded the scope to encompass various human-robot arrangements, including co-located, remote, and group settings [1]. Researchers have also delved into human-robot teaming theory, system design, efficient interaction methods, and communication strategies [2-4].

With the progression of computer vision technologies and artificial intelligence, skeleton tracking algorithms [5-6] have brought a brand-new solution to shape the future of HRI in space exploration. In essence, skeleton tracking employs depth cameras to observe and analyze human movements [7]. These depth cameras can discern a human from the surrounding environment and identify the position of joints, such as shoulders, knees, elbows, hands and fingers. Once identified, specialized software can translate these joints into a humanoid skeleton and track their movement in real time. This joint movement data becomes instrumental in controlling interactive robots for the purpose of conducting space exploration. (Figure1). The primary task in skeleton tracking is to develop an advanced skeleton tracking algorithm aimed at remotely controlling robot manipulators. As illustrated in Figure 1, this algorithm enables precise tracking of the operator's elbow, wrist and hand gestures in real time, facilitating seamless manipulation tasks. Consider a scenario where an astronaut is tasked with exploring a hazardous and volatile environment. Through the implementation of this innovative skeleton tracking algorithm, the astronaut can remotely control an onsite robot to execute missions by demonstrating gestures. By eliminating the need for physical presence in perilous environments or direct contact with hazardous objects, this approach guarantees the safety of the astronaut. Establishing several short-term objectives can lead to the achievement of these goals:

a. Utilizing three Intel RealSense depth cameras to construct a sophisticated 3D skeleton tracking system.

b. Developing an advanced tracking algorithm through machine learning coupled with homogeneous transformation;

c. Assessing the functionality of this skeleton tracking system in real-world space human-robot interaction scenarios, leveraging the Universal UR3e robot available in our lab. In the long term, our aim is to expand the scope of this project towards the development of an autonomous system. Specifically, we aspire to create an exploration robot endowed with multi-system autonomy. This endeavor aims to establish a sustainable and interoperable ecosystem capable of facilitating in-site resource utilization (ISRU), thereby supporting on-surface supply chain maintenance and enabling surface assembly and construction for space exploration.

## Methods and Procedures

The project employs both hardware implementation and tracking modelling methods.

### Hardware Implementation Method

As depicted in Figure 2, first, we will set up a skeleton tracking system by placing three Intel RealSense depth cameras around astronaut Figure 2a. Then, MediaPipe Pose [8], a machine learning solution, will be utilized to generate skeleton tracking functions Figure 2b. Communication with the onsite robot will be achieved using the Robot Operating System (ROS) Figure 2c. A Universal UR3e robot available in our lab will be used to validate the project idea Figure 2d.

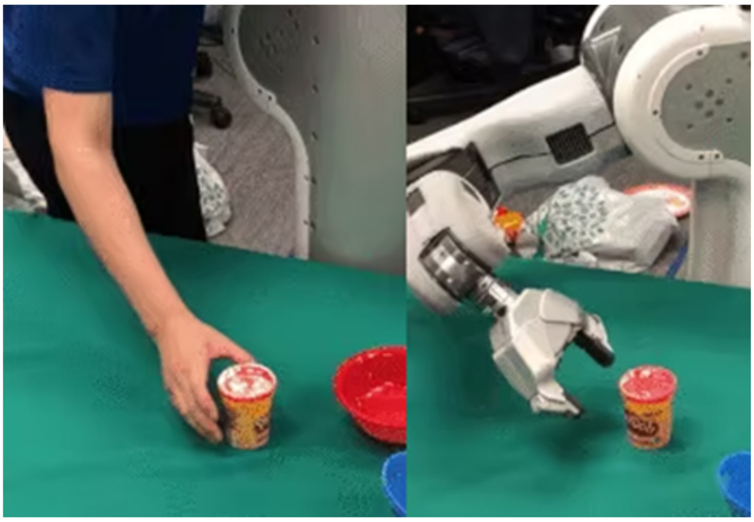

**Figure 1:** Robot Learning from Demonstration.

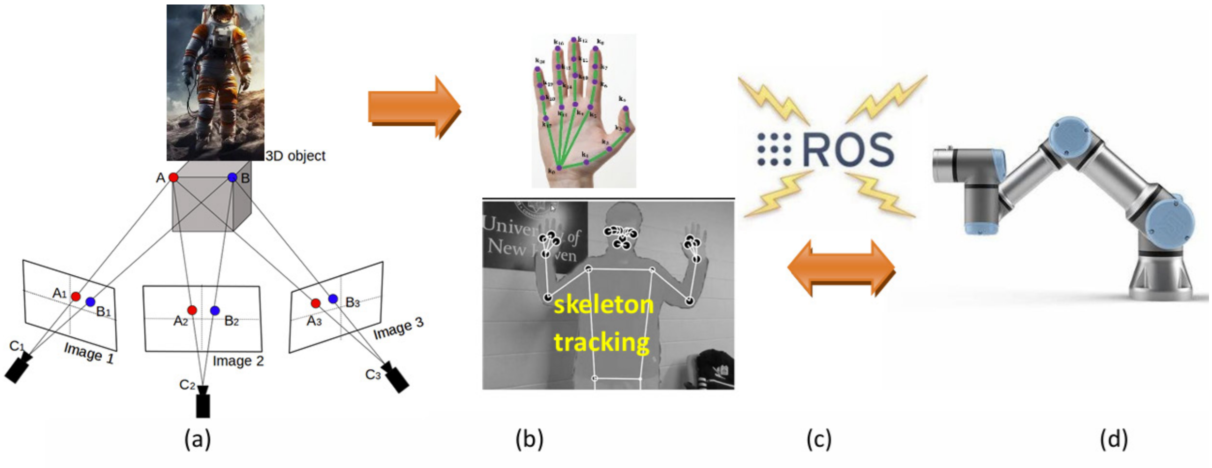


**Figure 2:** Schematic Diagram of the Tracking System.

## Tracking Modelling Method

Skeleton tracking is the process of understanding gesture communication. Head nodding, body postures, hand, and figure movements are effective means of communication in human interaction. In the realm of HRI, we aim to describe and understand human gestures so that their robot partner can follow and act accordingly. For this purpose, we need to develop a mathematical interpretation model. The modelling method is described below: (Figure 3).

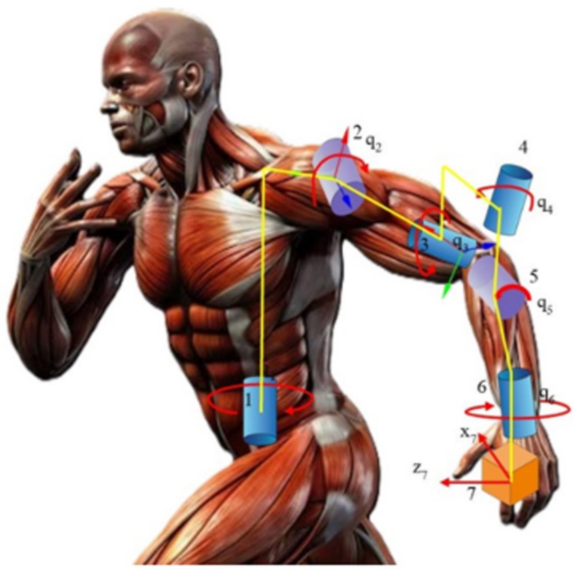

**Figure 3:** Skeleton Joints with Coordinates.

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The first step is to obtain the raw gesture data, including the pose of the operator's skeleton and detailed hand gesture as shown in Figure 2b, from the Intel RealSense depth cameras. Since MediaPipe produces 2D images, we propose using the weighted Delaunay triangulation algorithm to reconstruct the 3D image of the motion.

Let $S^{(w)}$ be a set of weighted points in $\mathbb{R}^3$.Let $p^{(w)} = (p, w_p), p \in \mathbb{R}^3$, $, w_p \in \mathbb{R}$and $z^{(w)} = (z, w_z), z \in \mathbb{R}^3, w_z \in \mathbb{R}$two weighted points. A weighted point $p^{(w)} = (p, w_p)$ can also be seen as a sphere of center p and radius $w_p$.The power product between $p^{(w)}$and $z^{(w)}$is defined as

$$\Pi(p^{(w)}, z^{w}) = ||p - z||^2 - w_p - w_z$$

where ||p-z|| is the Euclidean distance between $p$ and $z$. $p^{(w)}$ and $z^{(w)}$ are said to be *orthogonal* if $\Pi(p(w), z(w)) = 0$. The second step is to interpret astronaut's gestures based on the 3D images. For that purpose, the coordinates need to be assigned to the joints of the astronaut's skeleton, which are comparable to the cobot joints, as shown in Figure 3. The degrees of freedom (DoF) of the skeleton arm are labeled as qi, with i = 1, 2, …9. The Denavit-Hartenberg (DH) method is used to model the forward kinematics of the skeleton. The homogenous transformation matrix $H^{\backslash sw}$ of the wrist center of the skeleton coordinate system with respect to the base coordinate of the astronaut is expressed as follows: (Figure 4).

$$H^{sw} = \begin{bmatrix} n_x^{sw} & o_x^{sw} & a_x^{sw} & p_x^{sw} \\ n_y^{sw} & o_y^{sw} & a_y^{sw} & p_y^{sw} \\ n_z^{sw} & o_z^{sw} & a_z^{sw} & p_z^{sw} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

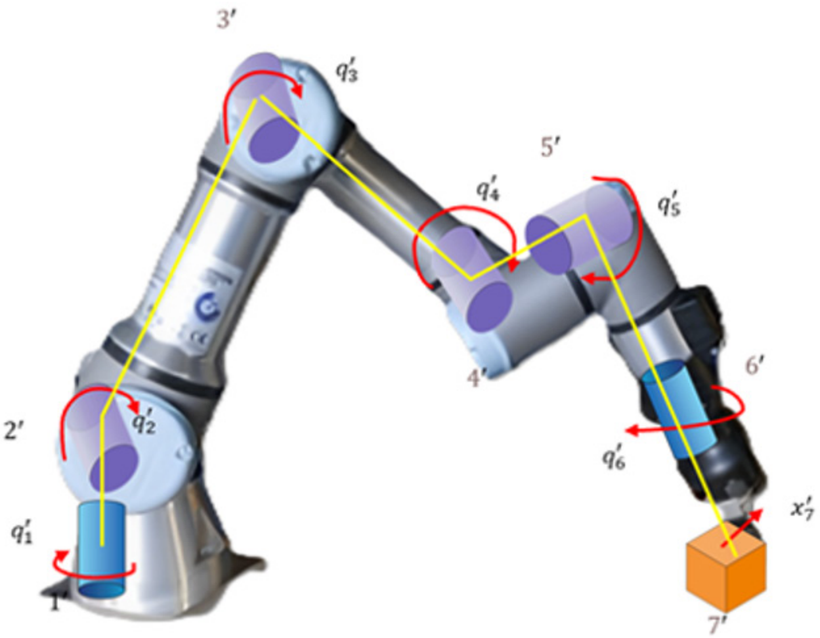


**Figure 4:** Cobot Joints with Coordinates.

where *sw* stands for the wrist of the skeleton $\boldsymbol{p}^{sw} = (p_x^{sw}, p_y^{sw}, p_z^{sw})$ is the position vector of the skeleton wrist with respect to the base coordinate system$(n_x^{sw}, n_y^{sw}, n_z^{sw}), (o_x^{sw}, o_y^{sw}, o_z^{sw})$,and $(a_x^{sw}, a_y^{sw}, a_z^{sw})$ are the rotations of the coordinates of the *sw* with the base coordinates.

The third step involves mapping poses between the astronaut and the UR3e cobot. Similar to the previous step, each DoF of the cobot joint needs to be described first, as illustrated in Figure 4. For the cobot, each joint is labeled as $q'_i$, with i = 1, 2, …9. Each $q_i$ is mapped with its corresponding $q_i$ in the skeleton. The mapping transformation matrix H^m between the skeleton and the cobot holds the following relation:

$$H^m = H^{sw} (H^{cw})^{-1}$$

where $H^{cw}_{\square}$ is the homogenous transformation matrix describing the wrist center of the cobot coordinate system with respect to the base coordinate of the cobot. By multiplying the skeleton-cobot transformation matrix $H^m$ with the homogenous transformation matrix $H^{\backslash sw}$, $H^{cw}$ can be derived as follows:

$$H^{cw} = H^m H^{sw} = \begin{bmatrix} n_x^{cw} & o_x^{cw} & a_x^{cw} & p_x^{cw} \\ n_y^{cw} & o_y^{cw} & a_y^{cw} & p_y^{cw} \\ n_z^{cw} & o_z^{cw} & a_z^{cw} & p_z^{cw} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where *cw* stands for wrist center of the cobot, $\boldsymbol{p}^{cw} = (p_x^{cw}, p_y^{cw}, p_z^{cw})$ is the position vector of the wrist center with respect to the cobot base coordinate system, $(n_x^{cw}, n_y^{cw}, n_z^{cw})$, $(o_x^{cw}, o_y^{cw}, o_z^{cw})$, and $(a_x^{cw}, a_y^{cw}, a_z^{cw})$ are the rotation of the coordinates of the cobot wrist with respect to its base coordinates.

The fourth step is to accomplish the mapping between the hand gesture with the operation of gripper of the cobot. The hand landmarks of the MediaPipe image are shown in Figure 5. We propose to use two formulas described below to determine the gestures of the fingers and the thumb:

$$finger = d(w,t) - d(w,k) + d(k,t) - 0.05$$

$$thumb = arcos(\frac{d(k,t)^2 + d(w,k)^2 - d(w,t)^2}{2d(k,t)d(w,k)}$$

where d(w,t) is the distance between the wrist and the figure tip, d(w,k) is the distance between the wrist and the knuckle, and d(k,t) is the distance between the knuckle and the figure tip. By determiningthe finger and thumb values, we can further determine the open and close operation of the gripper of the cobot.

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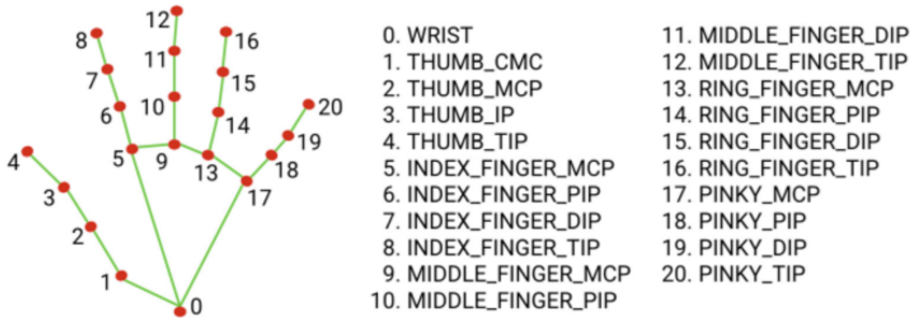


**Figure 5:** MediaPipe Hand Landmarks.

## Significance

This research inquiry holds significant relevance within the Exploration System Development Mission Directorate (ESDMD) [9]. Specifically, it aligns closely with NASA's Extravehicular Activity and Human Surface Mobility Program, which prioritizes the development of safe, reliable, and effective spacewalking and surface mobility capabilities. These capabilities are crucial for enabling astronauts to venture beyond the confines of their spacecraft. This research inquiry focuses on the development of a system that empowers astronauts to manipulate objects in space without direct physical contact, thereby prioritizing the safety of exploration endeavors. Moreover, the skeleton tracking algorithm under development holds promise for potential applications in collaborative space operations, particularly in the realm of human-robot teaming [10].

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