Anthropomorphic manipulator master-slave teleoperation using 3D depth sensor and color camera

V I Petrenko, F B Tebueva, M M Gurchinskiy, N Yu Svistunov, A K Nestulya
North-Caucasus Federal University, Stavropol, Russia
E-mail svistunovn4@gmail.com

Abstract. The article proposes a method for anthropomorphic manipulator teleoperation based on data processing using depth and color cameras of the Kinect controller. Processing data with Kinect allows to determine the coordinates of the nodal points of the operator’s body, which, after recalculation, can be used to generate control signals for the manipulator. The article describes the algorithm and the mathematical apparatus for determining the angles of the operator’s arm joints in real time. The proposed method can be used to control the joints of the manipulator of an anthropomorphic robot, and can also be adapted to control manipulators with a kinematic structure different from the structure of human arm, or to implement other control methods such as gesture control.

Keywords: Anthropomorphic manipulator, master-slave teleoperation, Kinect, depth sensor, joint angles.

1. Introduction
Recently, there has been a great interest in the topic of replacing a person when carrying out work in dangerous environments, emergency situations, and heavy routine work in industry. According to International Federation of Robotics, one of the directions in this field is the teleoperation of an anthropomorphic robot (AR) [1]. The teleoperation is based on the simultaneous motion trajectories formation for all degrees of freedom of AR manipulators using some kind of motion capturing device, e.g. an exoskeleton [2]. The use of AR teleoperation in undetermined and extreme environments is relevant because the human natural intelligence as a system for analyzing working conditions and decision-making still cannot be replaced with the artificial intelligence.

In addition to the growing demand for industrial robots in general [3], one of the trends in the development of robotics is the use of the motion tracking systems based on the depth sensors to capture operator’s movements. The aim of the work is to increase the convenience of the AR teleoperation through using motion capturing techniques. We develop an anthropomorphic manipulator teleoperation method using the Kinect controller to determine the coordinates of the operator’s body nodal points. The calculations of the kinematics are based on the methods described in [4], [5].

The study [6] examined the use of sensory information for automation systems. The capabilities and applications of motion capture technologies in robotics are described in the review [7], including control systems based on depth and color cameras, which are used in agriculture for harvesting [8], in medicine [9] for rehabilitation, and in interactive control systems based on gestures [10], [11].

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In [12], the Microsoft Kinect depth sensor is used to capture human movements: walking and turning. Unlike bulky motion capture suits, the sensor makes the system more convenient for the operator. Data on the position of the skeleton joints is extracted from Kinect and then processed to determine the joints angles of the robot.

2. Materials and methods

The Kinect controller (Figure 1), originally developed by Microsoft for the Xbox 360 game consoles family, is equipped with an RGB video camera, as well as an infrared emitter and receiver, which allow building a depth map and tracking object coordinates in three-dimensional space with a frequency of 30 Hz.

![Figure 1. Sensors and coordinate system of the Kinect controller](image)

Kinect software development kit allows to obtain the coordinates of the main nodal points of human body in real time (Figure 2). The coordinates of the right shoulder (8), left shoulder (4), as well as the elbow (5) and the wrist (6) of the operator’s left arm are used to organize the teleoperation of the anthropomorphic manipulator.

Anthropomorphic manipulator teleoperation with Kinect involves the following steps:
1. Acquiring the coordinates of the shoulder, elbow and wrist of the operator.
2. Transition to the coordinate system associated with the shoulder of the left arm.
3. Operator’s arm joints angles calculation.
4. Command formation for the manipulator.

The kinematic scheme of the operator’s arm and the anthropomorphic manipulator is shown in Figure 3, where $B_1 - B_3$ are the humeral, ulnar, and wrist points; $A_i$ is the wrist center point; $A_1 - A_7$ – rotational kinematic pairs. The coordinate system $A_1x_0y_0z_0$ is considered as global. The location of the coordinate systems associated with the links is selected in accordance with the Denavit-Hartenberg (DH) representation, the DH parameters are listed in Table 1. $L_1$ and $L_2$ are lengths of $B_1B_2$ and $B_2B_3$ links respectively.

We use the following notation: $^{i}T_{j}$ is homogeneous transformation matrix from the $j$-th to the $i$-th coordinate system, $i < j$, compiled in accordance with the DH representation;

$$^{i}T_{j} = \prod_{k=i+1}^{j-1}A_k, i < j$$

$$^{i-1}A_i = T_{z,\theta}(\theta_i)T_{x,a}(a_i)T_{x,a}(a_i),$$

$$T_{x,\theta}(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$
\[ T_{zd}(d) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \]

\[ T_{xa}(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \]

\[ T_{xa}(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) & 0 \\ 0 & \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \]

where $A_l$ is the homogeneous matrix of the complex transformation for adjacent coordinate systems; $T_{z\theta}(\theta)$ is homogeneous matrix of elementary rotation about the $z$ axis by the angle $\theta$; $T_{zd}(d)$ is homogeneous matrix of elementary shift along the $z$ axis by the distance $d$; $T_{xa}(\alpha)$ is homogeneous matrix of elementary shift along the $x$ axis by the distance $a$; $T_{xa}(\alpha)$ is homogeneous matrix of elementary rotation about the $x$ axis by the angle $\alpha$.

$T_l$ is the matrix of transformation from the $l$-th coordinate system into the global coordinate system. This matrix can be found by the following formula:

\[ T_l = A_l T_{i-1}, i > 0. \]

In the text the first, the second and the third components of a certain vector $V$ are denoted as $V_x, V_y, V_z$, respectively.

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**Table 1.** DH parameters of the manipulator and operator’s arm

| Link | $\theta_i$, degrees | $d_i$, cm | $a_i$, cm | $\alpha_i$, degrees | Range of $\theta_i$, degrees |
|------|----------------------|-----------|-----------|---------------------|-----------------------------|
| 1    | 0                    | 0         | 0         | -90                 | -180…90                     |
| 2    | -90                  | 0         | 0         | 90                  | -90…90                      |
| 3    | 90                   | $L_1$     | 0         | 90                  | 0…180                       |
| 4    | 90                   | 0         | 0         | 90                  | 20…180                      |
| 5    | 90                   | $L_2$     | 0         | 90                  | 0…180                       |

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Figure 2. Skeleton joint points captured by the Kinect controller.
3. Operator’s arm joint angles calculation

The radius vectors of points $B_1$, $B_2$, and $B_3$ in the coordinate system of the Kinect controller are denoted as $B_1''$, $B_2''$, $B_3''$ respectively, and the radius vector of the right shoulder is denoted as $B_0''$. It is assumed that the operator is facing the Kinect. In this case, the vector connecting the right and left shoulders may not be parallel to the $x$ axis of the Kinect coordinate system (but it should be parallel to the $xz$ plane). Therefore, to go to the global coordinate system $A_1x_0y_0z_0$, it is necessary to subtract the vector $B_1''$ from $B_2''$ and $B_3''$, and rotate the resulting vectors around the $y$ axis by the angle opposite to the angle $\phi$ between the projection of the vector $B_1''$ to the $xz$ plane and the positive direction of the $x$ axis:

$$\phi = -\text{atan2}(B_0''_x - B_1''_x, B_0''_z - B_1''_z),$$

(8)

where $\text{atan2}(a,b)$ is the function that returns the angle between the radius vector of a point $(a,b)$ and the positive direction of the abscissa axis, while the angle is counted in the direction from the abscissa axis to the ordinate axis and has a value in range from $-180^\circ$ to $180^\circ$.

The rotation matrix about the $y$ axis by the angle $\alpha$ is

$$M_y(\alpha) = \begin{pmatrix} \cos \alpha & 0 & \sin \alpha \\ 0 & 1 & 0 \\ -\sin \alpha & 0 & \cos \alpha \end{pmatrix}. $$

(9)

The transformed radius vectors $B_1'$ and $B_2'$ are denoted by $B_1^'$ and $B_2^'$, respectively:

$$B_1' = M_y(-\phi)(B_1'' - B_1''),$$

(10)

$$B_2' = M_y(-\phi)(B_2'' - B_1'').$$

(11)

The relative orientation of the Kinect coordinate system and the global coordinate system $A_1x_0y_0z_0$ after performing the offset and rotation transformations is shown in Figure 4. Thus, the homogeneous coordinates $B_1^0, B_2^0, B_3^0$ of the radius vectors of points $B_1$, $B_2$ and $B_3$ in the global (zero) coordinate system are

$$B_1^0 = (0 \ 0 \ 0 \ 1)^T,$$

(12)

$$B_2^0 = (B_2''_y \ -B_2''_x \ -B_2''_z \ 1)^T,$$

(13)

$$B_3^0 = (B_3''_y \ -B_3''_x \ -B_3''_z \ 1)^T.$$  

(14)
The angle $\theta_1$ is calculated by the formula

$$\theta_1 = \arctan \left( \frac{B_{2y}^0}{B_{2x}^0} \right) - 180^\circ. \quad (15)$$

With known angle $\theta_1$, the transition to the coordinate system associated with the first joint can be performed:

$$B_2^1 = (T_1)^{-1}B_2. \quad (16)$$

The angle $\theta_2$ is the angle between the positive directions of the axes $x_1$ and $x_2$ and can be found from the coordinates of the radius vector $B_2^1$:

$$\theta_2 = \arctan \left( \frac{B_{2y}^1}{B_{2x}^1} \right) + 90^\circ. \quad (17)$$

The vector $B_2B_3$ in the coordinate system associated with the second link is denoted as $B_2^3B_3^3$ and can be found according to formula

$$B_2^3B_3^3 = (T_2)^{-1}(B_3^0 - B_2^0). \quad (18)$$

The angle $\theta_3$ can be calculated as the angle between the projection of the vector $B_2^3B_3^3$ onto the $x_2y_2$ plane and the positive direction of $x_2$ axis:

$$\theta_3 = \arctan \left( \frac{(B_2^3B_3^3)_x}{(B_2^3B_3^3)_y} \right). \quad (19)$$

The value of $\theta_4$ is the angle between vectors $B_2B_3$ and $B_2B_1$:

$$\theta_4 = \arccos \left( \frac{(B_2^0 - B_3^0) \cdot (B_2^0 - B_1^0)}{|B_2^0 - B_3^0| |B_2^0 - B_1^0|} \right). \quad (20)$$

When calculating the angles $\theta_1$, $\theta_2$, $\theta_3$ using formulas (15)–(19), the angle $\theta_3$ can be outside the range $[0; 180^\circ]$. This is due to the fact the angles $\theta_1$ and $\theta_2$ may be found based on $B_2$ coordinates in more than one way. An invalid value of $\theta_3$ indicates that the wrong solution was chosen. In this case, the values of $\theta_1$, $\theta_2$ and $\theta_3$ should be adjusted as follows:

$$\theta_1^* = \begin{cases} 
\theta_1 & \text{if } \theta_3 > 0, \\
\theta_1 + 180^\circ & \text{otherwise};
\end{cases} \quad (21)$$

$$\theta_2^* = \begin{cases} 
\theta_2 & \text{if } \theta_3 > 0, \\
-\theta_2 & \text{otherwise};
\end{cases} \quad (22)$$

$$\theta_3^* = \begin{cases} 
\theta_3 & \text{if } \theta_3 > 0, \\
\theta_3 + 180^\circ & \text{otherwise},
\end{cases} \quad (23)$$

where $\theta_1^*$, $\theta_2^*$, $\theta_3^*$ are corrected values of the angles $\theta_1$, $\theta_2$, $\theta_3$.

After performing these calculations, a command for the manipulator is generated. It contains vector $\theta$ of the joints angles:

$$\theta = \{\theta_1^*, \theta_2^*, \theta_3^*, \theta_4\}. \quad (24)$$

Next, the calculation process is repeated for newly incoming input datasets from the Kinect controller.

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**Figure 4.** Kinect coordinate system relation to the global coordinate system

[Diagram of the coordinate systems and angles.]
4. Discussion
The proposed method for determining the angles of the operator’s arm joints using the Kinect controller allows to perform real-time anthropomorphic manipulator teleoperation. However, this method does not involve control of the end effector of the manipulator due to the difficulty of achieving acceptable accuracy. This problem can be solved through the use of haptic gloves.

When the elbow angle value $\theta_4$ is close to 180°, the accuracy of determining the angle $\theta_3$ can be reduced significantly, since the length of the vector $\overrightarrow{B_2B_3}$ projection onto the plane $x_2y_2$ becomes close to zero. In this case, the angle $\theta_3$ can be considered equal to the default value from Table 1, or fixed at a value calculated before the angle $\theta_4$ crossed the threshold (for example, 165°). Also in this case $\theta_3$ can be forecasted [13].

The depth and RGB cameras may be applied as an additional mean to the exoskeleton-based teleoperation systems [14] and during the human-robot cooperation in uncertain working environment [15-16].

5. Conclusion
In this paper the method for determining the joints angles of the operator’s arm in real time using the Kinect controller was proposed. The method can be used to implement anthropomorphic manipulators teleoperation. It does not require expensive wearable equipment and makes the teleoperation more convenient for the operator. Also, it can be modified to control manipulators with a kinematic structure different from the structure of human arms, and to develop other control methods based on motion capture (e.g. using gestures).

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