The Design of Intelligent Grasping Control System for a Special Operation Manipulator

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Abstract. In this paper, the control system of intelligent grasping for a special operation manipulator is designed to complete disaster relief, fire fighting, explosive disposal and the like for replacing human beings. The control system of the special operation manipulator is needed to have the characteristics of multiple terminal functions, accurate end accuracy and high system reliability and redundancy within outdoor environment. It puts forward higher requirements for the manipulator performance and operator. After analyzing the work requirements of the manipulator, the D-H parameters and motion space is calculated for further research. The forward and inverse kinematics models are built to make the control system into reality. The target grasping is achieved by using the force and position hybrid control and single joint/end control methods. The intelligent recognition system based on machine learning is constructed. The simulation training based on machine learning is carried out by using the back image of the end camera of the manipulator to help the operator locate the target quickly and accurately. Finally the special operation manipulator is used to carry out the target intelligent grasping experiment based on visual guidance. The test results show the effectiveness of the control system design. Thereby it is suitable to be promoted to other robot or manipulator control system design.

1. Introduction
The terrorist attack presents a new situation with complex and changeable environment, diversified forms and high scientific and technological content. Traditional means could not fully meet the needs of anti-terrorism security. Special operation manipulator could be applied to reduce casualties and improve mission success rate dealing with different types of tasks and environments. Special operations manipulator could shed a vital role in the field of disaster detection, rescue, biochemical detection, road clearance and car bomb detection [1-3].

The research of special operation manipulator is extensive, including executing agency, measuring and positioning technology, intelligent control technology, multi-sensor information fusion technology, visual guidance technology and so on. Some special operation manipulators suitable for certain situations have been developed by some famous companies and research institutes, such as Hunter developed by British researcher, the TEODOR produced by Telerob in Germany, RMI-9WT robot from Pedesco company in Canada, Lizard from Shenyang Institute of Automation Chinese Academy of Sciences in China, Super-DII-type developed by Shanghai jiaotong university in China and the like [4-7].

In this paper, a kind of special operation manipulator control system is studied. After analyzing the
work requirements of the manipulator, the D-H parameters and motion space is calculated for further research in section 2. The forward and inverse kinematics models are built to make the control system into reality in section 3. In section 4, the target grasping is achieved by using the force and position hybrid control and single joint/end control methods. At the same time, the intelligent recognition system based on machine learning is constructed, as well as the simulation training based on machine learning is carried out by using the back image of the end camera of the manipulator to help the operator locate the target quickly and accurately. Finally the special operation manipulator is used to carry out the target intelligent grasping experiment based on visual guidance.

2. Development of work

For satisfying the application requirement of special operation manipulator, the selected mechanism contains 4 degrees of freedom, two of which is used to change the attitude of the manipulator while the other two is the direction and open angle freedom of the ender. The mechanism brief diagram is shown in figure 1 which is without the open angle freedom of the ender [8]. In figure 1, $XY$ is the world coordinate system and $X_0Z_0$ manipulator coordinate system.

![Figure 1. The mechanism brief diagram](image)

Where:

$L_1 = 400mm$, $L_2 = 4mm$, $L_3 = 65.6mm$, $L_4 = 410mm$

Afterward the D-H coordinate system is set up using the standard D-H method shown in Table 1.

| $i$ | $\alpha_{i-1}$ | $a_{i-1}$ | $d_i$ | $\theta_i$ |
|-----|----------------|-----------|-------|------------|
| 1   | 0              | 0         | 0     | $\theta_1 + 0.573$ |
| 2   | 0              | $L_1$     | $-L_3$| $\theta_2 + 90 - 0.573$ |
| 3   | -90           | 0         | $L_2$ | $\theta_3$ |

Relying on the above analysis, the working space of the manipulator is calculated with Matlab simulation shown in figure 2. That indicates the design could fully meet the extension length requirement of operation manipulator application [9].

![Figure 2. The working space of manipulator](image)
3. Forward and inverse kinematics modeling

3.1. Forward kinematics modeling

The zero position of manipulator is the starting position defined as follows in figure 3. When the manipulator is fully expanded, the joint 1 is 120 degree, at the same time the joint 2 is -60 degree and joint 3 remains zero degree.

![Figure 3. Zero position definition](image)

While the operator needs to get the end position information of the manipulator, it is necessary to calculate the forward kinematics according to the real-time position of the first two joints obtained by reading the encoders of the joints. The real time angles of joints is named as $\theta_1$ and $\theta_2$. The coordinates of the end of the manipulator is as follows.

\[
x = L_1 \times \cos(\theta_1 + \theta) - L_2 \times \sin \alpha_2 \times \cos(\theta_1 + \theta) \times \sin(\frac{\pi}{2} + \theta_2 - \theta)
+ \sin(\theta_1 + \theta) \times \cos(\frac{\pi}{2} + \theta_2 - \theta)
\]

\[
y = L_1 \times \sin(\theta_1 + \theta) - L_2 \times \sin \alpha_2 \times \sin(\theta_1 + \theta) \times \sin(\frac{\pi}{2} + \theta_2 - \theta)
- \cos(\theta_1 + \theta) \times \cos(\frac{\pi}{2} + \theta_2 - \theta)
\]

Where: $\theta = \frac{0.573 \pi}{180}$, $L_1 = \sqrt{l_1^2 + l_2^2}$, $L_2 = l_4$.

Thus the end position x and y of the manipulator could be obtained by inputting the angle value.

3.2. Inverse kinematics modeling

It is crucial to pay attention to the initial posture and rotation direction of each joint during the inverse kinematic calculation. It is decouple of the joint 3 from the inverse kinematics of joint 1 and 2. The inverse kinematics of the manipulator is solved by geometrical method. Inverse kinematics is solved in two cases in coordinate system $X, Y, Z$ : the end point in second quadrant and in third quadrant. The mechanism brief diagrams of the above two situations are shown in figure 4.

![Figure 4. Inverse kinematics modelling situations](image)
The actual position of joints driven by the corresponding motors is as follows based on the kinematics modelling and the electrical zero definition when \( y > 0 \).

\[
\theta'_1 = a \tan 2(y, x) - \arccos \frac{L_1^2 - L_2^2 + x^2 + y^2}{2L_1 \sqrt{x^2 + y^2}} - \theta
\]

\[
\theta'_2 = -\arccos \frac{L_4^2 + L_2^2 - x^2 - y^2}{2L_4 L_2} + \theta
\]

Where: \( \theta = \frac{0.573\pi}{180} \).

While \( y < 0 \), the corresponding position of joints is as below.

\[
\theta'_1 = 2\pi + a \tan 2(y, x) - \arccos \frac{L_1^2 - L_2^2 + x^2 + y^2}{2L_1 \sqrt{x^2 + y^2}} - \theta
\]

\[
\theta'_2 = -\arccos \frac{L_4^2 + L_2^2 - x^2 - y^2}{2L_4 L_2} + \theta
\]

3.3. Inverse kinematic feasibility analysis

When the end position is operated in Cartesian coordinate system, the end position is calculated by the current joint position and then adjusted according to the instructions issued by the operator. Through inverse kinematics, the angles of each joint are calculated and executed. The feasibility analysis mainly includes two aspects. The one is whether the given end position has exceeded the scope of work space. The other one is whether the joint position obtained is beyond the range of joint motion. For the first case, it could be detected by calculating the distance between the end position and the origin of base coordinate system. The inverse kinematics would be handled when the end position \((x, y)\) meets the limits as behind. Otherwise the feedback information would be given that the manipulator is out of work range [10].

\[
\sqrt{x^2 + y^2} < 0.75m \quad (x < 0, y > -0.1m)
\]

For the second case, the angle of each joint is checked before execution. If it is not beyond the scope of work, the output will be executed. Or else the message will be given that joint is out of the scope of work.

4. Intelligent grasping control system design

4.1. Single joint and end control system design

The single joint and end control technology is mainly switched according to the different task requirements of the special operation manipulator. In this paper, it is adopted with the force and position hybrid grasping control technology and single joint/end control technology. The end of manipulator could be moved forward and backward in X direction as well as up and down in Z direction for the two degrees of freedom of manipulator. The movement in the Z direction is limited while the target is on the uneven surface. The hardware of manipulator or the target will be caused damaged if all of the joints are forced to approach the target. Therefore, it could be carried out position control in the Y direction under the manipulator coordinate system while the force control in Z direction for grasping the target with two sets of parallel complementary feedback [11]. The force and position hybrid control principle is showed in figure 5.
The force and position control is controlled by different control strategies for force and position respectively. The task space is divided into force control space and position control space complementarily. By selecting the matrix to determine the current contact force and position control direction, force and position feedback information are got back to the corresponding loop respectively for force and position control simultaneously in the restricted motion. Each operation of the manipulator could be broken down into several sub-jobs. For each sub-job, a constraint coordinate system \{c\} could be used to define a generalized surface. It is defined as the position constraint along the normal direction of the surface accordingly the force constraint the tangent direction. Generally \{c\} have the following characteristics:

- \{c\} is a rectangular coordinate system to describe of the operation conveniently.
- Depending on the assignment, \{c\} may be moved with the end of the manipulator or fixed with base.
- \{c\} has two degrees of freedom to be decomposed into force and position control along each of the degree at any time.

### 4.2. Intelligent identification system design

The intelligent identification system based on machine learning is proposed in this paper. The machine learning model is trained to analyze whether there is a target in the field of view, thus helping the operator to locate the target quickly and accurately. The end of the special operation manipulator is equipped with a camera to obtain training data. Firstly, Gaussian blur algorithm is used to remove noise and make the image smooth and easy to deal with. Then, through Canny edge detection algorithm, the edge of the target is identified, which is retained as candidate target. By using the HoughLine algorithm to calculate the target angle, the feature of the target is retained by machine learning algorithm [12]. Finally, the target is grasped with the special operation manipulator. The identification process is shown in figure 6.

The edge gradient is calculated by the blow algorithm.

\[
\begin{align*}
G_x(x, y) & \approx [S(x, y+1) - S(x, y)] + [S(x+1, y+1) - S(x+1, y)]/2 \\
G_y(x, y) & \approx [S(x, y) - S(x+1, y)] + [S(x, y+1) - S(x+1, y+1)]/2
\end{align*}
\]

(8)
According to the gradient of x and y direction, the gradient amplitude and Angle of the image can be calculated. The edge selection is implemented based on the double threshold method, thus Canny edge detection is completed.

\[
\begin{align*}
G(x, y) &= \sqrt{G_x^2(x, y) + G_y^2(x, y)} \\
\theta(x, y) &= \tan^{-1}\left(\frac{G_y(x, y)}{G_x(x, y)}\right)
\end{align*}
\]  

(9)

Through the Hough transform line detection, a series of straight lines are obtained to determine the general direction of the target. Because of the complex texture region and noise influence, there are many different linear directions, so it is necessary to find the main direction of the target. In this paper, the pixel space of 360 degrees is divided into \( m \) parts, and then the number of straight lines in each interval is counted. The maximum angle range is set as the main direction. Due to the complexity of environmental background, the candidate target obtained by edge detection is necessary to be identified by machine learning in figure 7.

![Figure 7. Machine learning process](image)

The special operation manipulator with camera at the end is carried on the mobile platform. At the beginning of the task, the mobile platform firstly moves to the target to make the target located within the grasp of the manipulator. Using a single camera, the collected images are transmitted back to the mobile vehicle platform. After the machine learning and calculation, the target position and grasping path are obtained. The framework of visual processing system is shown in figure 8.

![Figure 8. The framework of visual processing system](image)

5. Results and validation
Using the special operation manipulator to grasp the target, the position, speed and current curve of each joint were monitored, as well as the current changes before and after grasping the target. The position, velocity and current curves are shown in figure 9.
(a) Actual measured position, velocity and current curves of joint 1
(b) Actual measured position, velocity and current curves of joint 2

Figure 9. Actual measured position, velocity and current curves

Current control mode is adopted to grasp the target. In excess of the set current constant value, the claw will maintain constant force grasping to ensure the safety of the target. The change curves of the position, speed and current are shown in figure 10.

Compared with the actual performance curve and design parameters of the special operation manipulator, the design of the control system of the special operation manipulator is proved effectively. It is suitable to be promoted to other robot or manipulator control system design.

Figure 10. The current control mode grasping

6. Conclusion
In this paper, the control system of intelligent grasping for a special operation manipulator is designed to replacing human beings. After analyzing the work requirements of the manipulator, the D-H parameters and motion space is calculated. Then the forward and inverse kinematics models are built to make the control system into reality. After that, the target grasping is achieved by using the force
and position hybrid control and single joint/end control methods. The intelligent recognition system based on machine learning is constructed. The simulation training based on machine learning is carried out to help the operator locate the target. Finally the special operation manipulator is used to carry out the target intelligent grasping experiment based on visual guidance. The test results show the effectiveness of the control system design. Thereby it is suitable to be promoted to other robot or manipulator control system design.

The further research is needed to make the algorithms more efficient for the complex environment, as well as the real time performance of the algorithms and control system is also needed to be improved in future research.

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References
[1] Shin Y J, Lee H J, Kim K S, et al. A Robot Finger Design Using a Dual-Mode Twisting Mechanism to Achieve High-Speed Motion and Large Grasping Force[J]. IEEE Transactions on Robotics, 2012, 28(6):1398-1405.
[2] Palli G, Natale C, May C, et al. Modeling and Control of the Twisted String Actuation System[J]. IEEE/ASME Transactions on Mechatronics, 2013, 18(2):664-673.
[3] Wilson J M, Joy J M, Lowery R P, et al. Effects of oral adenosine-5′-triphosphate supplementation on athletic performance, skeletal muscle hypertrophy and recovery in resistance-trained men[J]. Nutrition & Metabolism, 2013, 10(1):57.
[4] Song G. Self-Localization System of the Explosive Ordnance Disposal Robot based on Danger Model Immune Wavelet Neural Network[J]. International Journal of Digital Content Technology & Its Applications, 2013, 7(1):643-651.
[5] Li Zenggang, ADAMS entry Explanation and examples [M], National Defense Industry Press,2006.
[6] R.L. Norton,Design of Machinery, McGraw Hill, 2011.
[7] W. Zhang, J. Yuan, J. Li, Z. Tang, “The Optimization Scheme for EOD Robot Based On Supervising Control Architecture,” Proc. of the 2008 IEEE International Conference on Robotics and Biomimetics, Bangkok, Thailand, February, 2009.
[8] K. Massey, J. Sapp, and E. Tsui, “Improved Situational Awareness and Mission Performance for Explosive Ordnance Disposal Robots,” Unmanned Systems Technology XI, edited by G.R. Gerhart, D.W. Gage, C.M. Shoemaker, Proc. of SPIE Vol. 7332, 2009.
[9] R. krogh, J. Peng Jin. dynamics of structures[M].Bei Jing, Higher Education Press, 2010.
[10] Wang Y, Li K, Zhou H, et al. Dynamic analysis and co-simulation ADAMS-SIMULINK for a space manipulator joint[C]// International Conference on Fluid Power and Mechatronics. IEEE, 2015:984-989.
[11] N. Pouliot, P. Latulippe and S. Montambault, and S. Tremblay,“ Reliable and Intuitive Teleoperation of LineScout: a Mobile Robot for Live Trans-mission Line Maintenance,” The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, Missouri, October 2009.
[12] Yanbo Wang, Ke Li, Haiping Zhou, Songbo Deng, Jian Xu and Jiayu Liu , Dynamic Analysis and Co-simulation ADAMS-SIMULINK for a Spatial robotic manipulator Joint [J], IEEE International Conference on Fluid Power and Mechatronics, 2015.