Collaborative robot manipulator control in dynamic environment using computer vision system

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Abstract. This paper provides the trajectory planning and motion control scheme for collaborative robot manipulator in a dynamic environment using the computer vision system. The key result is a real-time motion control algorithm using potential fields approach. The simulation results illustrate the performance of the proposed algorithm. As a test platform, the KUKA iiwa manipulator is used.

1. Introduction
Collaborative robots are designed to work with humans. Accordingly, the many safe operation challenges about avoiding collisions in a dynamic environment are relevant [1]. There are several approaches to achieve this; first, an energy- and power-based approach [2] that deals with adjusting parameters of an impedance controller using various safety metrics [3], and second, trajectory planning approaches trying to answer the question "how to change the motion to avoid collision or safely contact with the environment".

The provided algorithm is based on the results presented in [4] and [5]. In the paper [4], a control method using computer vision was proposed. In paper [5], a method for planning a trajectory based on potential fields was proposed. The main result of the presented work is integrating the visual servo control method and trajectory planning with the impedance controller within the framework of a unified control system. The synthesis method for dynamic controllers, together with the visual control method, was presented in [6]. Thus, it is ensured that the manipulator tool follows the target object, which is in the field of view of the RGB-camera installed on the last link of the manipulator, with a deviation from the goal trajectory of movement in proportion to the external force.

2. Problem formulation
The task is to follow a visual target using a collaborative robot manipulator with an eye-in-hand RGB-camera and unknown stationary and movable obstacles in the robot environment.

The Lagrangian dynamics equation for robot is given as:

$$M(q)\ddot{q} + N(q, \dot{q}) + J^T(q)f_{\text{ext}} = u,$$  \hspace{1cm} (1)

where $M(q)$ is the robot inertia matrix, $N(q, \dot{q}) = C(q, \dot{q}) + g(q) + h(q, \dot{q})$, $C(q, \dot{q})$ is the Coriolis and centrifugal forces matrix, $g(q)$ is the gravity vector, $h(q, \dot{q})$ is the friction forces vector, $f_{\text{ext}} \in \mathbb{R}^6$ is the external forces vector and torques applied to the robot manipulator body, $u$ represents the torques acting on the joints, $q, \dot{q}, \ddot{q}$ are generalized coordinates, velocities and accelerations.
vectors, \( f(q) \) is the Jacobian, expressed with respect to the tool. The external force \( f_{ext} \) can be measured by a force sensor or estimated from the measurements of joints’ torques.

The control goal is given in the form
\[
\|e(t, f_{ext})\| \leq k \Delta(f_{ext}), \quad \text{for} \ t > T,
\]
where \( e(t, f_{ext}) = x_f(t, f_{ext}) - x(t) \) is the control error, \( x(t) \in \mathbb{R}^6 \), \( x_f(t, f_{ext}) \in \mathbb{R}^6 \) are the current and desired position of the robot manipulator tool, \( \Delta(f_{ext}) \) is proportional to the action of the external force and the constant parameter \( k > 0 \), \( T \) is the settling time.

3. Methods

In accordance with [4] and considering \( f_{ext} \), the control goal (2) can be provided by a controller of the following form:
\[
u = f^\top(q)\alpha + \hat{M}(q)\ddot{q} + \hat{C}(q, \dot{q})\dot{q} + \hat{g} + f_{ext},\tag{3}\]
where \( \alpha = \hat{\lambda}(q)\left[\ddot{x}_f + M_v^{-1}\left(K_p(\dot{x}_f - \dot{x}) + K_p(x_f - x)\right)\right] \), \( x_f, \dot{x}_f, \ddot{x}_f \) is tool trajectory generated using potential fields, \( K_p, K_D \) and \( M_v \) are diagonal matrices of stiffness, damping and virtual mass of impedance controller, \( \hat{M} \) is estimation of the inertia matrix, \( \hat{C} \) represents Coriolis and centrifugal forces, \( \hat{g} \) is the gravitational term, \( u \) is control signals vector.

Trajectory planning taking into account possible obstacles is implemented using a potential fields method, where the virtual force is the sum of the attractive \( f_a \) and repulsive \( f_r \) terms are defined as:
\[
f(x_f, x^*, x_0) = f_a(x_f, x^*) + \sum_k f_r(x_f, x_{o_k}).\tag{4}\]

Let us write the equation describing the dynamics of target and obstacles as mass-spring-damper system considering the action of external forces on the robot manipulator tool:
\[
M_v\ddot{x}_f + K_v(x^* - x_f) + D_v\dot{x}_f + K_ef_{ext} = f_r(x_f).\tag{5}\]
where \( x^* \) is a target spatial position of robot manipulator tool generated by image-based visual servoing approach that can be written as:
\[
\dot{x}^* = -\lambda(LV)^+(s - s^*),\tag{6}\]
where \( s \in \mathbb{R}^{2m} \) and \( s^* \in \mathbb{R}^{2m} \) are the vectors of the current and desired position of the moving target in the camera image space, \( m \) is the number of visual features of the target object, \( L \) is the image Jacobian, \( V \) is the adjoint matrix for transformation between robot manipulator base and tool, \( \lambda > 0 \) is a gain.

By integrating (5) and expressing the variable \( x_f \), the desired trajectory of the robot manipulator tool can be obtained at each time interval \( t \in [t_k, t_{k+1}] \):
\[
x_f(t_{k+1}) = x_f(t_k) + \int_{t_k}^{t_{k+1}} M_v^{-1}(f_r - K_v(x^* - x_f) - D_v\dot{x}_f)dt + \dot{x}_f(t_k)dt.\tag{7}\]

To implement the trajectory planning algorithm, it is necessary to consider velocity limits, which can be defined as:
\[
\dot{x}_f(e_f) = \begin{cases} 
0.5(v - \delta)\left(1 - \cos\left(\frac{e_f}{e_1}\frac{\pi}{2}\right)\right) + \delta, & e_f \geq e_1, e_f < e_2 \\
v_f, & e_f < e_1 \\
0.5(v - \delta)\left(1 - \cos\left(\frac{e_f - e_2}{e_1 - e_2}\frac{\pi}{2}\right)\right) + \delta, & e_f > e_2, e_f < (1 - \delta) \\
0, & \text{otherwise}
\end{cases}\tag{8}\]
where $v$ is the maximum velocity, the constants $c_1$ and $c_2$ set the boundaries of acceleration and deceleration, the normalized distance on the current segment of the trajectory is given as:

$$e_f = \frac{x_f - x^*}{\|x_0 - x_f\| + \|x_f - x^*\|}.$$  \hfill (9)

Hence, it can be seen that when a physical or virtual contact occurs, the algorithm provides braking with a simultaneous displacement of the robot manipulator tool in the direction of the total repulsive force vector $f_r$ and the velocity vector $\hat{x}_f$. The direction of the vector is determined depending on the type of interaction. For the case of virtual interaction, the angle between the force and velocity vectors can be written as:

$$\varphi = \arccos \frac{-f_r \times \hat{x}_f}{\|f_{\text{ext}}\| \|\hat{x}_f\|}. \hfill (10)$$

When approaching an obstacle, simultaneously with a change in the direction of movement, it is necessary to reduce the velocity, that can be written as:

$$k_v,\dot{x}_f(\varphi) = \begin{cases} 1 - k_0 \cos (\varphi \pi) + 1, & \text{if } \varphi \in [-\pi, \pi] \end{cases} \hfill (11)$$

where, to ensure smooth velocity it is necessary to define scaling factor

$$k_\alpha = \begin{cases} A \left( \frac{1 - \cos \left( \frac{\|f_r\| \pi}{f_{\text{max}}} \right)}{2} \right), & \text{if } \|f_r\| \leq f_{\text{max}}, \end{cases} \hfill (12)$$

where $f_{\text{max}}$ is the damping factor, $A > 0$ is a gain.

For the case of physical interaction, a monotonically decreasing function is introduced, which has a minimum if the force and velocity vectors are directed in opposite directions and a maximum when the directions coincide. Therefore, the scaling parameter is defined as:

$$k_{v,e} = g(f_{\text{ext}}, \hat{x}_f) \hfill (13)$$

Thus, the total scaling function can be written as:

$$k_v = \min\{k_{v,e}, k_v,\dot{x}_f\} \hfill (14)$$

Higher values of the gains of the $K_v$ matrix can provide faster convergence, while a decrease coefficients leads to more compliant movement, which is an advantage when the robot manipulator physically interacts with objects in environment. It is possible to achieve such a behavior of the system by introducing a variable matrix $K_v(e_f)$ that depends on the normalized distance to the target $e_f$ and can be defined as:

$$K_v(e_f) = \max\{K_{v,\text{max}}(1 - e_d)K_{v,\text{min}}\} \hfill (15)$$

4. Results

To validate the proposed control scheme, it was implemented in the Matlab/Simulink using the dynamics and kinematics parameters of the KUKA LBR iiwa robot. The simulation of a robotic arm was carried out using the recursive Newton-Euler method. The control schema overview is shown in the Figure 1.
The impedance controller parameters are given as:

\[ K_M = 0.01I_{7 \times 7}, K_D = 5I_{7 \times 7}, K_P = 10I_{7 \times 7}, \]
\[ M_v = 0.01I_{6 \times 6}, D_v = 10I_{6 \times 6}, K_v = 20I_{6 \times 6}, \]

where \( I_{n \times n} \) is the diagonal identity matrix, the initial configuration of the robot manipulator is defined as:

\[ q_0 = [0, -0.78540, 1.57080, 0.7854, -1.5708], \]

The initial and desired position of the visual target in the camera image space are defined as:

\[ p_0 = \begin{bmatrix} 416.31 & 416.31 & 616.31 & 616.31 \\ 404.12 & 604.12 & 604.12 & 404.12 \end{bmatrix}, \]
\[ p_d = \begin{bmatrix} 412 & 412 & 612 & 612 \\ 412 & 612 & 612 & 412 \end{bmatrix}. \]

The value of gain in (6) is defined as:

\[ \lambda = 8. \]

The simulation results are shown in the Figures 2-3.
5. Conclusion
A real-time trajectory planning and motion control algorithm based on potential fields that deals with virtual and external forces is proposed. The simulation results (see Figures 2-3) show that the presented trajectory planning and motion control algorithm ensure the achievement of the control goal (2) under the conditions of external forces acting on the robot. The application of the proposed algorithm is seen in tasks where the robot manipulator tool is tracking a moving visual target, for example, grasping items from a rotating or linear conveyor.

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