Intuitive Collision Avoidance of Robots Using Charge Generated Virtual Force Fields

Alexander Winkler and Jozef Suchý

Abstract. This article presents an approach to intuitive collision avoidance of hand-operated robots. Hand-operations are realized by means of zero-force impedance control using force/torque sensor. Impedance control is then combined with the method of artificial potential fields exerting force on the end-effector. This force can be felt by human, who acts on the manipulator and cooperates with the robot. The way to generate potential fields in this work is based on virtual electrical charges placed on the obstacle surfaces. In comparison with other approaches this method is quite universal and can be flexibly used for all forms of obstacles. It may be favourable to implement an additional artificial damping field to prevent hurting obstacles in the case of higher end-effector velocities. It is also possible to use this approach with moving obstacles. In this situation the charges would be placed dependent on sensor information provided e.g. by camera.

1 Introduction

To guarantee physical integrity of human operators, industrial robots usually worked behind safety fences. In the last several years the so called safety controllers were developed and they became more and more acceptable, [10]. The application of safety controllers permits human-robot interaction which means coexistence and collaboration between human and robot in the shared workspace, [7], [8].

One kind of human-robot interaction is hand-operation of robots by means of forces and torques affected by operators on the manipulator arm or end-effector. Forces and torques can be measured by force/torque wrist sensor or by joint torque sensors. Possible applications are assistance tasks where workpieces are handled

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jointly by human and robot. Furthermore, in this way the robot can learn and record a complex task from operator. Moreover, human-robot cooperation is not restricted just to industrial robots. It can be assigned also to service/domestic and to humanoid robots.

In this context it may by useful to consider obstacles and restrictions within the workspace in an intuitive manner. This means that in the present paper the operator feels physically boundaries when operating the manipulator. One method to realize this functionality is the integration of virtual potential fields in the workspace which will result in vector force fields acting on the robot. Using potential fields is a well known and investigated approach to planning paths of mobile or stationary robots, [3], [9]. However, it makes also sense to apply virtual force fields in real time during human-robot-interaction or robot-robot interaction. In comparison with commonly used methods to generate the artificial potential field [6] in this contribution the approach of virtual charges is preferred, because it is quite universal and can be used for almost all forms and combinations of obstacles. The common effect of using algorithms based on charges is their easy implementation in the robot controller in contrast to high computing time. Though, nowadays the relatively high available computing power makes this aspect more and more irrelevant.

In this paper the application of virtual force fields is focused to hand-operation of robots. For this reason the next section delivers short insight into the field of force guided or force controlled robots based on zero-force impedance control. Section 3 introduces the new approach to real time generation of virtual forces around obstacles and near restricted areas in the workspace. Within this approach due to the presence of wrist force and torque sensor the algorithm lets the operator physically feel the neighborhood of real or virtual obstacles. It is based upon virtual point charges placed on the obstacle surfaces. After implementation of hand-operation via impedance control and generation of the artificial force vector field, some experiments will demonstrate the performance of the algorithm. The presented algorithm may be improved by some additional features, e.g. by adding artificial damping field near obstacles [1], described together with other features in section 3. Finally, in section 4 the short conclusion is given.

2 Hand-Operation of Robot Manipulators

Hand-guiding or hand-operation of robots by a human operator acting by means of forces and torques on its end-effector or on the whole manipulator arm can be understood as a special kind of robot force control, namely the zero-force-control. For this purpose the robot is, as a rule, equipped with a wrist force/torque sensor or with joint torque sensors. So, hand-operation can be performed in Cartesian or in joint space. Another method is the estimation of the interaction forces and torques from the joint motor currents in the case when these values are available, [14]. Further approaches are possible in the future, e.g. the application of tactile matrices.

2.1 Hand-Guidance in Operation Space

With a six component force/torque sensor mounted in the robot wrist it would be obvious to control the robot in operation space. Measured interaction forces will result in linear motions of the robot tool, and interaction torques will generate rotations of the tool. The relationship between interaction forces/torques and robot behavior can be described by the general mappings $\mathscr{F}_v$ and $\mathscr{F}_\omega$

$$\mathbf{v} = \mathscr{F}_v(\mathbf{F}) \quad \text{and} \quad \omega = \mathscr{F}_\omega(\mathbf{T}) \tag{1}$$

where **F** and **T** are the vectors of measured interaction forces and torques, respectively. **v** is the vector of the linear velocity and ω represents the angular velocity of the tool frame. It will be also possible to compute the Cartesian interaction forces/torques in tool frame from measured values of joint torque sensors. This, however, seems not to be expedient because contact forces on the whole manipulator arm are then taken into consideration.

2.2 Hand-Guidance in Joint Space

A different behavior of the robot in comparison with the operation space approach can be achieved using the joint space approach to force guidance, [13]. For this purpose the interaction joint torques τ have to be measured by joint torque sensors. Alternatively, they can be calculated from measured values of force/torque wrist sensor using the geometric Jacobian matrix **J**:

$$\tau = \mathbf{J}^T \begin{bmatrix} \mathbf{F} \\ \mathbf{T} \end{bmatrix} \tag{2}$$

These joint torques will result in the motion of the particular joint similarly described by

$$\dot{\mathbf{q}} = \mathscr{F}_q(\tau) \; , \tag{3}$$

where $\dot{\mathbf{q}}$ is the vector of joint velocities.

The advantage of hand-operated robot arms in joint space is that the generated motion matches the expected motion of the particular mechanical system represented by its kinematics. Besides, it is eventually possible to pass singularities which divide the task space of the manipulator without any problem, [12].

2.3 Linear Impedance Dynamics of the Hand-Operated Robot

The relationship between interaction forces/torques and the robot motion can be understood as the enforced dynamics of the force controlled robot. Dynamics may be comparatively freely defined by control algorithms. However, some restrictions have to be taken into consideration. The parameters of this kind of dynamics have to match the dynamics of robot joint drives and the dynamics of operator to guarantee the safety.

The common version of robot dynamics during hand-guidance is the dynamics of mass-damper-system for each joint or each Cartesian degree of freedom. These virtual mass-damper-systems can be implemented in the robot controller by

$$\tau_i = M_i\ddot{q}_i + D_i\dot{q}_i \quad \text{or} \quad F_i = m_i\ddot{X}_i + d_i\dot{X}_i \tag{4}$$

for motion generation in joint space or in operation space. In (4) τ_i and F_i represent the interaction joint torques or the Cartesian interaction forces/torques, respectively. Robot joint angles are given by q_i and X_i are the Cartesian coordinates of the tool frame ($\dot{\mathbf{X}} = [v_x\ v_y\ v_z\ \omega_x\ \omega_y\ \omega_z]^T = [\mathbf{v}\ \omega]^T$). Whichever algorithm of hand-operation will be implemented its dynamic behavior can be adjusted by the parameters of virtual masses or mass moments of inertia m_i, M_i and damping coefficients d_i, D_i. Hence, the zero-force controlled robot is realized by special type of well known impedance control, [5].

3 Collision Avoidance Using Virtual Force Fields

Using hand-operation as a method of human-robot collaboration not desired collisions between robot and environment should be avoided. Especially, when contacting stiff surfaces high interaction forces may result in uncoordinated robot motions endangering the operator.

It would be preferable if the human interacting with the robot could feel obstacles during hand-guiding. One idea how to implement it is to make use of virtual forces emitted by the obstacles and boundaries. These forces act against the interaction force and show intuitively restrictions to the operator. The application of artificial potential fields is a well known and investigated approach to path planning of mobile and stationary robots, [3]. In contrast to scalar potential fields the application of vector force fields to human robot interaction induces a lot of new possibilities. They can be also combined with the impedance control of the robot.

3.1 Generation of Virtual Force Fields

Convenient approach to generate the virtual force fields within the robot workspace is based on virtual electric charges, which generate virtual electrostatic field in their neighborhood. The electrostatic force $\mathbf{F}_{12}$ between two charges Q_1 and Q_2 acts according to:

$$\mathbf{F}_{12} = -\frac{1}{4\pi\varepsilon}\frac{Q_1Q_2}{||\mathbf{r}||^2}\frac{\mathbf{r}}{||\mathbf{r}||} \tag{5}$$

In (5) ε represents the electric permeability and $\mathbf{r}$ is the position vector between the charges. The absolute force is reciprocally proportional to the square of the distance between both charges. However, for realization of virtual force fields this particular form of dependence is not obligatory and (5) can be generalized introducing force function $\mathscr{F}$:

$$\mathbf{F}_{12} = \mathscr{F}(||\mathbf{r}||)\frac{\mathbf{r}}{||\mathbf{r}||} \tag{6}$$

Hence, the function $\mathscr{F}$ describes the relationship between distance and virtual force.

For the generation of virtual force fields surrounding complex obstacles several charges are necessary. Let the number of charges be n. It will be favorable to place them on the whole surface of obstacle. In contrast to some other approaches taking the form of obstacles directly into consideration when generating the force field, this method is universal and easily programmable. Now, for the calculation of the virtual force $\mathbf{F}_V$ acting against the operator near obstacles the principle of superposition gives

$$\mathbf{F}_V = \sum_{i=1}^{n}\left(\mathscr{F}_i(||\mathbf{p}-\mathbf{e}_i||)\frac{\mathbf{p}-\mathbf{e}_i}{||\mathbf{p}-\mathbf{e}_i||}\right), \tag{7}$$

where $\mathbf{p}^T = [p_x\ p_y\ p_z]$ is the current position of the robot end-effector and $\mathbf{e}_i^T = [e_{x_i}\ e_{y_i}\ e_{z_i}]$ describes the location of arbitrary virtual charge with respect to the world frame. Force function $\mathscr{F}_i$ of each particular charge can be chosen individually. Nevertheless, it may be convenient to choose one common function for all charges.

When choosing hyperbolic or exponential force functions the absolute force has to be limited to avoid dangerous situations for the human operator. Furthermore, a maximum action distance between charge and end-effector should be defined. Outside of it the resulting force should be set to zero.

After processing the superposition of all force components the resulting virtual force vector $\mathbf{F}_V$ acts against the real interaction forces $\mathbf{F}_H$, thus giving rise to the resulting force $\mathbf{F}$:

$$\mathbf{F} = \mathbf{F}_H - \mathbf{F}_V \tag{8}$$

It does not seem to be expedient to generate virtual torques in the neighborhood of an obstacle although it might be possible. It can be anticipated that the reaction of the manipulator arm within the virtual force field depends on the mode of hand-guiding. Using hand-guiding in operation space will result in position changes only and the orientation of the tool will be kept constant. On the other side the joint space approach will cause orientation changes, too.

3.2 Hand-Guided Industrial Robot Influenced by Virtual Forces

To demonstrate the approach to intuitive collision avoidance a six axis articulated robot STÄUBLI RX90B was used. It is equipped with a 6-DOF JR3 force/torque wrist sensor to realize force guidance. The robot workspace can be seen in Fig. 1. There are a number of virtual charges placed on the ground floor and on the surface of the storage rack located on the left side. In the here presented case the distance between every two charges is $100mm$. This value was chosen to reduce computation time of the robot program running on the commercial CS7B robot controller. Obviously, the smaller distance would result in the smoother force field. The

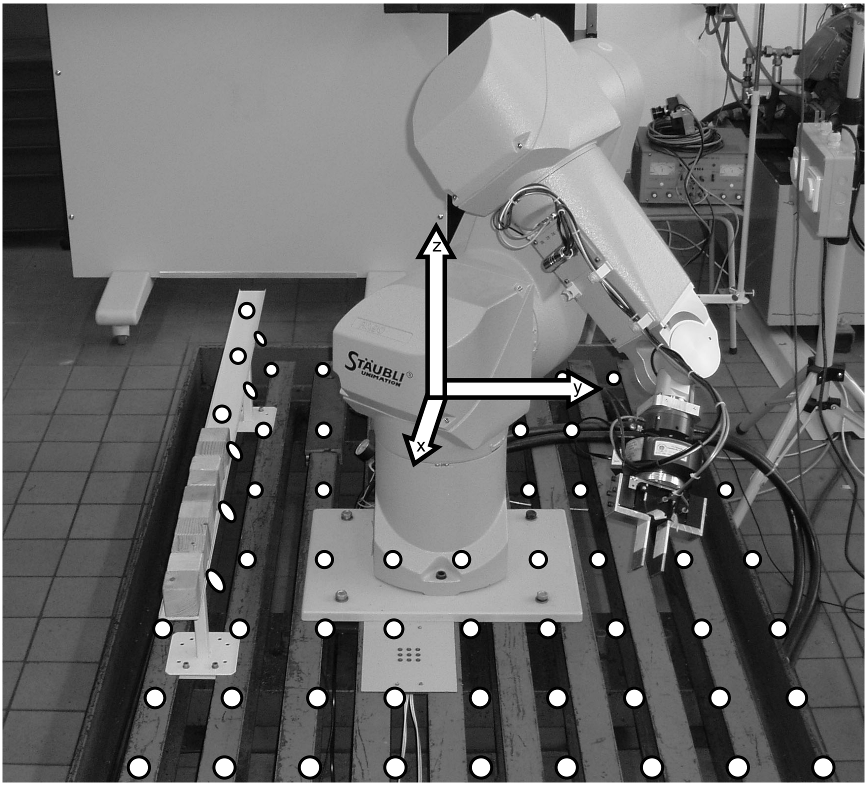

Fig. 1 Several virtual charges placed in the robot workspace.

force function of each charge is set to $\mathscr{F}(r) = 40000Nmm^2 \cdot r^{-2}$, where $r = ||\mathbf{p} - \mathbf{e}_i||$. The force effect of each individual charge is limited by the distance of $150mm$. The resulting force of all virtual charges is saturated to the value of $15N$.

Fig. 2 shows the force field in front of the robot generated by the charges placed on the ground floor located at $z = -400mm$ with respect to robot world frame. For this purpose the absolute value of the virtual force vector on different planes has been plotted. It can be seen that the maximum force value of $15N$ is reached at the distance of approximately $50mm$ between end-effector and charge layer. As can be seen, some valleys appear in the gaps between the charges. This effect may be reduced by increasing the number of charges.

The force in dependence of distance between the end-effector and the border of workspace can be seen in Fig. 3. For this purpose the y-coordinate is fixed to zero. Because of the point charges the force field is somewhat wavy. Nevertheless, this property will not downgrade the functionality of intuitive collision avoidance.

The functioning of this approach can be seen in Fig. 4. A human operates the manipulator by acting on its end-effector. The interaction force vectors are displayed by the dashed arrows. Close to the ground floor some charges are placed which

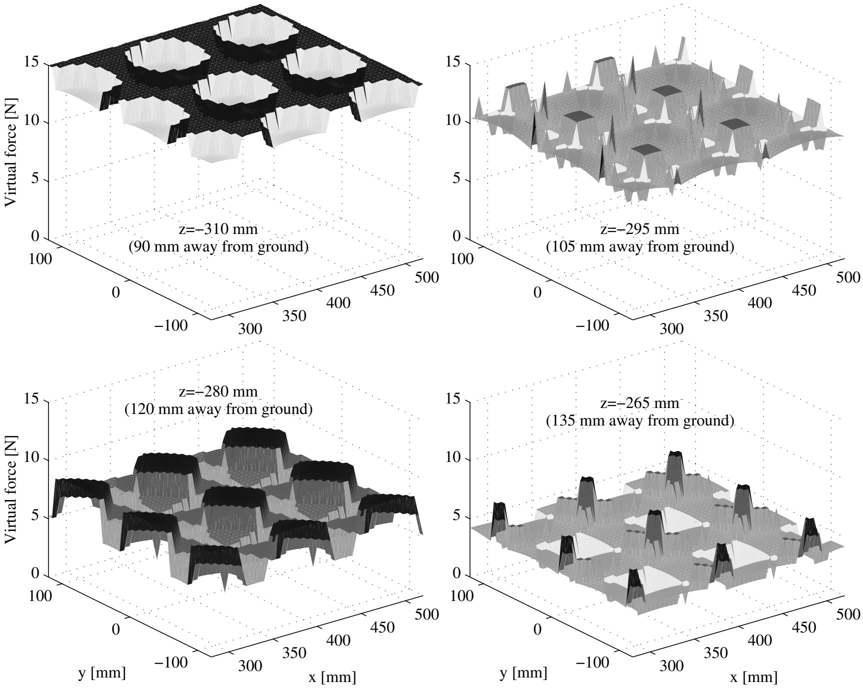

Fig. 2 Force field emitted by the ground floor charges on different distance planes.

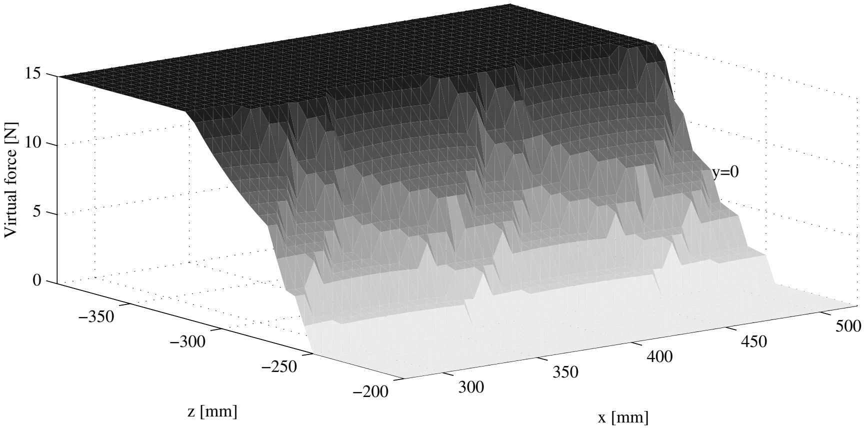

Fig. 3 Force field in dependence of obstacle distance.

generate the virtual force field. When the robot is guided closer to the obstacle the repulsive force increases. This can be seen observing the solid arrows. For better visualization the x-coordinate was kept constant by the operator. The combination

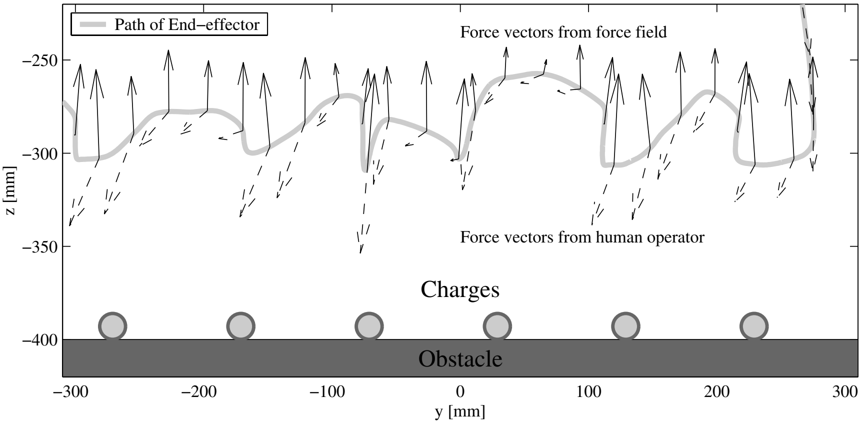

Fig. 4 End-effector path and force in the neighborhood of an obstacle with virtual charges.

of the human interaction force and the virtual force emitted by the charges, results in the corresponding end-effector path are also shown in Fig. 4.

3.3 Additional Aspects and Features

3.3.1 Limitation of Interaction Force Vector

Guiding the robot end-effector closely toward an obstacle a dangerous situation may occur if the interaction force is higher than the virtual repulsive force emitted by the obstacle. It is then possible that the end-effector crosses the charge layer and crashes into the object because behind the charge layer the direction of the virtual force vector suddenly changes. On the other side it will not be convenient to do without limitation of the force function when $r \longrightarrow 0$ because dangerous situations for the operator may also occur.

A very simple way to prevent overrun of the charge layer and crash is the saturation of the interaction force of the human operator. It has to be guaranteed that the maximum value of $||\mathbf{F_H}||$ is always smaller than the maximum value of $||\mathbf{F_V}||$. This can be easily realized in the robot program. The charge layer is then an insurmountable barrier and protects the object.

3.3.2 Virtual Damping Field

Another aspect which has to be taken into consideration is the following one: The force field may be seen as a variable virtual non-linear spring which brings the robot back into a position far away from the obstacles. Regarding the dynamics of the hand-guided robot defined in (4) together with the virtual spring the behavior of the manipulator will result in a non-linear spring-mass-damper system. If one considers the additional time delay of the human operating the manipulator and feeling the obstacles it may easily occur that the whole system begins swinging. In the worst case it will become unstable.

One approach to avoid this situation is the implementation of an additional virtual damping field generated by the method of point charges. The simplest way is that the virtual damping $\mathbf{d}_V$ depends directly on the virtual force $\mathbf{F}_V$:

$$\mathbf{d}_V = \left[d_{Vx} \; d_{Vy} \; d_{Vz} \right]^T = \mathbf{d}_V \left(\mathbf{F}_V \right) \tag{9}$$

As the result $\mathbf{d}_V$ will decelerate the current robot motion together with the dampings of the linear impedance dynamics from (4) and stabilize the system.

3.3.3 Sources of Virtual Fields

Until now the virtual charges were placed manually during implementation of the robot program. This method is applicable when the layout of the robot workspace is simple. Another way might be to use the data from CAD of robot work cell. Then the locations of the charges could be generated automatically.

Yet another possibility is collision avoidance between multiple moveable objects using virtual force fields, e.g. between two robots [2] or a robot and a movable mechanism. In this case the positions of the charges located on the movable obstacle are changing in every computation cycle. If so, the primary application of intuitive collision avoidance during hand-operation becomes secondary. The effect of the virtual force field can rather be seen as a kind of the so called non-contact impedance control, [11]. Using this approach with commercial industrial robots, standard motion control algorithms have to be combined with impedance control.

Besides the application of virtual force emitting robots to avoid collisions in robot-robot collaboration the here presented approach will be extended for the purpose of human-robot collaboration. The position of a worker in the robot work cell can be detected by a 3D-camera, [4]. After that the human will be ”cropped” with virtual force charges. The resulting force field will prevent the manipulator from touching the worker.

4 Conlusion

In this paper an approach to generating artificial force fields within the robot workspace has been presented. The source of the field is a set of charges which can be seen as electric charges. This force field can be applied to intuitively control collision avoidance when hand-operating the robot manipulator. If the robot is equipped with a wrist force/torque sensor and the human performs hand-operation by pushing or pulling the end-effector he or she feels the virtual force field and brings the robot away from the restricted areas. Usually the charges have to be placed on the surfaces of obstacles. Thus, this approach is quite universal and can be easily implemented. The algorithm presented here was successfully verified on an industrial robot hand-operated by a human.

In the next future further analysis concerning the force functions seems to be necessary. The number of charges and the force functions assigned to them determine the characteristics of the force field.

Besides human-robot collaboration an interesting scope of application may be the robot-robot cooperation in the shared workspace. In this case virtual force fields emitted by the robots will help to avoid their collisions. For this purpose the commonly used algorithms to control the robot motion have to be extended to include the non-contact impedance control.

Furthermore, additional sensor information may be combined with the presented approach to the force field generation. A camera or laser scanner can monitor the work cell during human-robot collaboration. Human worker generates the virtual force field by charges placed on his body to keep the robot away from himself. The location of the charges is modified during every interpolation cycle by the camera information.

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