Towards Exploiting Contacts for Dual-Arm Manipulation with Humanoid Robots

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Abstract—Dangerous tasks, which are ideal for robots, are extensively found in thousands of existing gloveboxes being used in nuclear facilities, and humanoid robots would be an attractive option to replace human hands owing to their ability to use tools built for humans. However, such tasks usually require manipulating heavy objects, such as debris and old tools, in a very confined space; thus, it would be challenging to perform manipulation tasks and balance the robot at the same time. In order to address this problem, we propose to exploit contacts with the glovebox and formalize the problem for planar case by omitting dynamics. We formulate the joint torques such that the robot is tried to be balanced in the redundancy of the task space. The proposed method is tested through simulations in a simplified scenario in which two arms with four revolute joints grasp a circular object at different positions. Our preliminary results show that the proposed method successfully moves the ZMP towards the center of the SP when the redundancy allows.

I. INTRODUCTION

Dangerous radioactive conditions prevail in thousands of existing gloveboxes in nuclear facilities. Each glovebox task requires at minimum three workers: an operator, a radiological control inspector, and a supervisor. In spite of strict safety procedures enforced in all DoE (US Department of Energy) operations, accidents do sometimes occur (http://goo.gl/xSbUKf). Human supervised robots may provide a safer and more effective means of carrying out these tasks.

Although a robotic system that is specifically designed for glovebox operations may be the best solution, humanoid robots are also an attractive option since they can operate in a variety of environments and use tools that are designed for humans. Figure 1 illustrates such a case with NASA’s humanoid robot Valkyrie [8] while her forearms are confined in a glovebox. In order to conduct operations within a glovebox with a robotic system, the constraints imposed by the nature of such operations and the structure of the environment must be taken into account. One option would be to use advanced motion planning and control algorithms [4, 6, 7, 10, 3] that would allow the system to avoid collisions and instability while performing manipulation tasks in the glovebox. Sugihara and Nakamura [9] analyze the stability and the arm manipulability for a two dimensional humanoid robot and show the relation between the degree of manipulability and the stability. In [2] investigates the case of pushing objects with a humanoid robot and shows its relationship with the zero-moment point excluding heavy objects. However, while manipulating heavy
objects, which is the usual case for such applications since they mostly require manipulating debris, old tools, etc., it could be challenging to find feasible motions while maintaining the robot’s equilibrium; moreover, these operations are held in a very confined space, so taking steps in arbitrary directions is usually not possible.

Toppling occurs when the zero-moment point (ZMP) leaves the support polygon (SP). In [5], an increase in support polygon size by using supplementary contact points is shown. Thus, we propose to exploit the contacts in the glovebox (i.e., leaning on the boundaries of the glovebox) rather than avoiding them in order to maintain the ZMP within the support polygon while performing manipulation tasks.

To study this scenario we design a simplified, planar environment for a dual-arm manipulation task within a glovebox. As shown in Fig. 2, we use the vertical plane for visual convenience, so the gravity acts in the negative y-direction. We consider a dual arm system, each with four revolute joints and assume the system is supported by a line contact with the ground. The objectives in this scenario are to grasp the object (i.e., the magenta circle) at a given pose, while ensuring the robot’s balance by exploiting supporting forces through contacts with the glovebox boundaries when needed, and to avoid undesired collisions between the robot and the environment at the same time. The goal of this paper is to formulate the problem of finding joint torques that would grasp the object at a desired pose and keep the ZMP at a desired point by utilizing the redundancy of the system by omitting velocities and accelerations (i.e., for quasi-static case).

II. METHODOLOGY

For the static equilibrium of the system, we need to consider the wrench due to the robot’s mass, the object’s motion generating wrench and the wrenches at the supporting contact points on the glovebox ports. The top and bottom arms in Fig. 2 are denoted as the first and second arms respectively. The system’s static equilibrium can be written as below:

\[
\sum f = 0 \Rightarrow f_R + mg + \sum_{i=1}^{n_s} f_{s_i} + \sum_{i=1}^{n_c} f_{c_i} = 0 \tag{1}
\]

where \( m \) is the total mass of the robot, \( \mathbf{g} \) denotes the gravity vector given by \( \mathbf{g} = [0, -9.8]^T \), \( \mathbf{f}_{s_i} = [f_{s_{i1}}, f_{s_{i2}}]^T \) denotes the force at the support points between the second link of the \( i \)-th arm and the glovebox port, \( \mathbf{f}_{c_i} = [f_{c_{i1}}, f_{c_{i2}}]^T \) denotes the forces at the contact points between the object and the \( i \)-th end effector. \( \mathbf{f}_R = [f_{R_{x}}, f_{R_{y}}]^T \) denotes the ground reaction force. \( n_c \) and \( n_s \) are the numbers contact points on the object and the supporting contact points on the glovebox ports, respectively.

For static equilibrium, the moment about the \( z \)-axis (i.e., in-plane direction) at the origin of the world frame \( O \) must be zero:

\[
M^z_O = 0 \Rightarrow \mathbf{p}_R^T S^T \mathbf{f}_R + \mathbf{p}_{CoM}^T S^T mg + \sum_{i=1}^{n_s} \mathbf{p}_{s_i}^T S^T \mathbf{f}_{s_i} + \sum_{i=1}^{n_c} (\mathbf{p}_{c_i}^T S^T \mathbf{f}_{c_i} + M^z_{c_i}) = 0 \tag{2}
\]

where \( \mathbf{p}_R, \mathbf{p}_{CoM}, \mathbf{p}_{s_i}, \) and \( \mathbf{p}_{c_i} \) are the vectors denoting the position of the ground reaction force i.e. whose \( x \) component corresponds to the ZMP, the robot’s center of mass (CoM), the support points on the glovebox ports and the contact points on the object, respectively. \( M^z_{c_i} \) is the moment at the contact points between the object and the \( i \)-th end effector, and \( \mathbf{S} \) is the cross product matrix that is used to perform the cross product operation between position and force vectors to obtain the moment about \( z \)-axis such that the positive direction is counterclockwise, given by:

\[
\mathbf{S} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{3}
\]

\( \mathbf{p}_R \) is obtained by solving Eqs. (1) and (2) simultaneously. In order to avoid toppling the ZMP must lie between the robot’s feet; in other words, the moment at the front foot must be positive and the moment at the rear foot must be negative. Similarly, we can calculate the support force for the \( i \)-th arm, \( \mathbf{f}_{s_i} \), for a desired ZMP position.

The object wrench \( \mathbf{h}_{obj} \in \mathbb{R}^3 \) can be obtained in terms of the wrenches at grasp points \( \mathbf{h}_c \in \mathbb{R}^{3n_c} \) as follows:

\[
\mathbf{h}_{obj} = [\mathbf{W}_{c_1} \cdots \mathbf{W}_{c_{nc}}] \begin{bmatrix} \mathbf{h}_{c_1} \\ \vdots \\ \mathbf{h}_{c_{nc}} \end{bmatrix} = \mathbf{W}_c \tag{4}
\]

where \( \mathbf{W}_{c_i} \in \mathbb{R}^{3 \times 3} \) is the wrench matrix that transforms the wrench at the contact point \( c_i \), \( \mathbf{h}_c \in \mathbb{R}^3 \), to the wrench at the origin of the object frame, that is the center of the circular object in this case, and given by:

\[
\mathbf{W}_{c_i} = \begin{bmatrix} \mathbf{I}_2 & 0_{2 \times 1} \\ \mathbf{S}^T \mathbf{r}_{c_i} & 1 \end{bmatrix} \tag{5}
\]

where \( \mathbf{r}_{c_i} \) is the vector from the \( i \)-th contact point \( c_i \) to the origin of the object frame, \( \mathbf{I}_m \) is the \( m \times m \) identity matrix, and \( 0_{m \times n} \) is the zero matrix of size \( m \times n \). Given the object wrench we can calculate the wrenches at the contact points

![Fig. 2. Glovebox environment.](image-url)
from \( h = W^+ h_{obj} \), where \( W^+ \in \mathbb{R}^{3n_c \times 3} \) is the Moore-
Penrose pseudo-inverse of the matrix \( W \in \mathbb{R}^{3 \times 3n_c} \).

Hence, given a joint configuration i.e. assuming the robot is already in contact with the object and the desired support points, we can calculate the joint torques, \( \tau \), that satisfy the given object wrench as:

\[
\tau = \begin{bmatrix} J^T_{c_1} & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & J^T_{c_{n_c}} \end{bmatrix} W^+ h_{obj} = J^T W^+ h_{obj}
\]

(6)

where \( J_{c_i} \in \mathbb{R}^{3 \times n_{d_i}} \) is the Jacobian matrix for the \( i \)-th arm, where \( n_{d_i} \) is the number of degrees of freedom (DOF) of the arm, and \( J \in \mathbb{R}^{3n_c \times \sum n_{d_i}} \) is the complete Jacobian matrix.

Furthermore, we can exploit the system’s redundancy (i.e., the null space of \( J^T W^+ \)) to obtain a supporting force at the glovebox ports in order to slide the ZMP towards a desired location, as follows:

\[
\tau = J^T W^+ h_{obj} + \left[ I_{\sum_i n_{d_i}} - J^T W^+ (J^T W^+) \right] \tau_{ZMP}
\]

(7)

where \( \tau_{ZMP} \) is the vector of torques that has non-zero elements only at the elements corresponding to the first \( n_g \) joints of the arms that is between the base of the arms and the glovebox ports, which can be calculated as following as a function of the force at the support points that would move the ZMP to a desired position, which can be calculated by solving Eqs. (1) and (2) simultaneously for the support forces:

\[
\tau_{ZMP} = \begin{bmatrix} J^T_{s_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & J^T_{s_{n_s}} \end{bmatrix} \begin{bmatrix} f_{s_1} \\ \vdots \\ f_{s_{n_s}} \end{bmatrix}
\]

(8)

where \( J_{s_i} \) is the translational Jacobian matrix of the \( i \)-th arm from the base to the point that contacts with the support point on the glovebox; e.g., in this case it is given by:

\[
J_{s_i} = \begin{bmatrix} \partial o_x/\partial \theta i_1 & \partial o_x/\partial \theta i_2 & 0 & 0 \\ \partial o_y/\partial \theta i_1 & \partial o_y/\partial \theta i_2 & 0 & 0 \end{bmatrix}
\]

(9)

where \( \theta_{ij} \) and \( d_{ij} \) are the angle and length of the \( i \)-th joint link on the \( i \)-th joint and \( i \)-th joint link contact point to obtain a force only in y-direction; and to grasp the circular object, we select the top and bottom points on the object as contact points. We assume that the robot (excluding the arms) has a mass of 50 kg with its CoM is at the position where are the first joints of the arms are located (i.e., robot’s base), and each link on the arm has a mass of 0.5 kg, a length of 0.5 m and its CoM at the middle, and the object has a mass of 10 kg (i.e., \( h_{obj} = [0, -10g, 0]^T \)).

In order to show that our method is able to move the ZMP towards the desired point (i.e., the center of the SP in this case) using the redundancy of the task space, we show results for two different object poses and robot configurations: first, when the object’s center is 1.2 m away from the robot’s base in the \( x \)-direction; second, when the object’s center is 1.8 m away from the robot’s base in the \( x \)-direction.

The result for the first case is shown in Fig. [3]. It is seen that the ZMP when the robot does not lean on the glovebox is quite close to the SP boundary (i.e., only 0.014 m away from the front foot). Ideally, we need 295.92 N force to move it to the desired point; however, when we use the null space of the manipulation task, we are only able to generate a force of 167.64 N that moves the ZMP ca. 0.1 m left, which seems sufficient to do the task safely.

In the second case, the ZMP (or rather the fictitious ZMP (11)) is already out of the SP when the robot does not lean on the glovebox, and to move it to the center of the SP, we need 424.24 N force in vertical direction at the support point. Nevertheless, the null space allows us to generate only 228.04 N. As a result, the ZMP shifts slightly (i.e., 5 mm) inside the SP, and this does not provide us a satisfactory safe region in the SP to perform the task safely; yet, the top arm could be used to obtain additional support.

### III. Results & Discussion

For simulations, we assume point contacts without friction for all contact points; we select the point below the second arm as the support point and lie its second link horizontally on the contact point to obtain a force only in y-direction; and to grasp the circular object, we select the top and bottom points on the object as contact points. We assume that the robot (excluding the arms) has a mass of 50 kg with its CoM is at the position where are the first joints of the arms are located (i.e., robot’s base), and each link on the arm has a mass of 0.5 kg, a length of 0.5 m and its CoM at the middle, and the object has a mass of 10 kg (i.e., \( h_{obj} = [0, -10g, 0]^T \)).

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### IV. Conclusion

In this study, we consider a humanoid robot that performs dual-arm manipulation tasks in a glovebox. Since such tasks usually require manipulating heavy objects, such as debris and old tools, in a very confined space; it would be challenging to perform manipulation tasks and balance the robot at the same time. In order to address this problem, we propose to lean on the boundaries of the glovebox and formalize the problem for planar case by omitting dynamics. Our method tries to avoid...
toppling of the robot in the redundancy of the task space. The proposed method is tested through simulations in a simplified scenario in which two arms (each with four revolute joints) grasp a circular object at different positions. The preliminary results demonstrate that the method successfully moves the ZMP towards the center of the SP when the redundancy allows. Future work includes taking into account the dynamics and actuator limitations.

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