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Short communication

The concept of mobility in single- and double handed manipulation

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ABSTRACT

The concept of mobility describes an important property of the human body when performing manipulation tasks. It describes, in a sense, how easy it is to accelerate a link or a point on the manipulator. Most often it is calculated for the end-link or end-point of the manipulator, since these are important for the control objective of the manipulator. Mobility is the inverse of the inertia experienced by a force acting on the end-point, or a combined force and torque acting on the end-link. The concept has been used in studies of reaching tasks with one arm, but thus far not for bi-manual manipulation. We present here the concept for both single-handed and double-handed manipulation, in a general manner which includes any type of grip of the hands on the object. The use of the concept is illustrated with data on the left and right arm in a golf swing.

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1. Introduction

The concept of end-point mobility in a robotic or human manipulator was introduced by Hogan in three seminal papers on impedance control (Hogan, 1985a,b,c). The mobility represents the inertial behavior of the manipulator, and is the inverse of the inertia tensor for the end-point. A controller (human or automatic) may make use of this concept to control the manipulator such that the end-point shows larger resistance to disturbances in some directions. Hogan wrote

> The physical meaning of the end-point mobility tensor is that if the system is at rest (zero velocity) then a force vector applied to the end-point causes an acceleration vector (not necessarily co-linear with the applied force) which is obtained by pre-multiplying the force vector by the mobility tensor.

It should be noted that a force acting on a *moving* manipulator will experience additional resistance due to velocity-dependent terms in the equations of motion. Think about the resistance to changes in orientation of the axis of a spinning wheel. Hogan's papers on impedance control deal with the problem of controlling a manipulator with significant dynamic interaction with the environment (the manipulated object). Humans perform such manipulation tasks with astonishing performance considering the significant signal delays and variability inherent in the neuro-muscular system. Hogan thus postulated (Hogan, 1984, 1985b) that humans obtain good performance by not only making the end-point follow a desired path, but by also modulating the inertia and stiffness of the end-point, i.e. by impedance control. The possibility of modulating the inertia (and mobility), stiffness and damping of the end-point/end-link is a feature of redundant manipulators. Modulation of stiffness and damping is made possible by co-activation of antagonists.

A considerable number of papers have used the concepts of impedance and mobility in the study of motor control of human reaching tasks. See, for instance Sabes et al. (1998), Hamilton and Wolpert(2002), Lametti et al. (2007), Selen et al. (2009), and Cos et al. (2011). The experimental condition has typically involved a model of the arm as a planar three-link mechanism. We are currently using the concept of mobility to gain insight into the motor control of fast and accurate bi-manual tasks, using the golf swing as the specific case. This case differs from single-limb reaching tasks in the important aspect that the two arms collaborate. Hogan derived the expression for the mobility based on the Jacobian of an open-chain, single arm manipulator, but did not consider the case of two-arm manipulation. Zatsiorsky (2002) also discusses the concept of end-effector mobility, but only for open kinematic chains. There is thus a need to extend the theory of mobility to double-handed grasping and manipulation.

The purpose of this short communication is to present the method of calculating the mobility both for the end-point and for the whole end-segment and for both single- and double handed

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manipulation in a unified way so that this interesting concept may be more accessible to researchers in biomechanics and motor control.

2. Kinematics and kinetics

The kinematics and kinetics of the human body are approximated by a mechanical linkage, i.e. a chain of rigid bodies connected by joints. The mechanism has a number of degrees of freedom (DoF), n, represented by a vector of generalized coordinates $q=[q_1\ q_2\ \dots\ q_n]$.

The human body interacts physically with the surroundings. We are here primarily concerned with manipulation, and hence focus primarily on the contact between the hands, or implements held by the hands, and the surroundings. Importantly, the interaction forces and corresponding displacement velocities at the contacts must be *energetically conjugate*, meaning that their inner product corresponds to the flow of energy (i.e. power) transferred to/from the system at the contact.

2.1. Jacobian

The *Jacobian* is the derivative of the forward map with respect to the generalized coordinates. The Jacobian for the manipulator gives the velocity V as a linear (but configuration-dependent) function of the generalized velocities $\dot{q}$

$$V=J(q)\dot{q}. \tag{1}$$

The velocity V may here refer to either the translational velocity of a point in three dimensions or the complete six-dimensional velocity of a rigid body.

2.2. The grasp map

The grasp is defined by which forces can be applied by the manipulator on the object. For instance, a point-contact on an object with friction-free surface can only apply a force normal to the surface of the object and directed towards the interior of the object.

The force on the object from a single contact becomes

$$F=G_1F_1,$$

where F and F_1 are both six-dimensional *wrenches* (Murray et al., 1994). The wrench F representing both the force f_b and the torque τ_b acting on a rigid body, i.e.

$$F=\begin{bmatrix} f_b \\ \tau_b \end{bmatrix},$$

where as

$$F_1=\begin{bmatrix} f_1 \\ \tau_1 \end{bmatrix}$$

is the wrench acting at the contact point between manipulator and object.

The grasp matrix G_1 for a single contact defines the possible forces and torques that can be transmitted through the contact (Murray et al., 1994). The matrix is a combination of (1) a projection onto the subspace of possible wrenches transmitted through the contact, and (2) a transformation of the wrench into the reference frame of the manipulated object. The latter transformation is a so-called *adjoint transformation* which rotates the force and torque vectors and adds a torque term $f_1\times d_1$, which is the torque generated by contact force f_1 acting at a distance d_1 from the origin of the object frame (often taken to be its center of mass).

When the grasp involves several contacts with the object, the total force on the object becomes

$$F=G_1F_1+G_2F_2+\dots+G_mF_m=[G_1\quad G_2\quad \cdots\quad G_m]\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix}.$$

The matrix

$$G=[G_1\quad G_2\quad \cdots\quad G_m]$$

is called the *grasp map*. For the case of two hands manipulating an object, the grasp map will be

$$G=[G_1\quad G_2].$$

The grasp map also relates the velocities at the contact-points and the velocity of the object. Consider the work performed by the resulting wrench F acting with velocity V on the object

$$\int_{t_1}^{t_2} V^{\mathrm{T}}F\,dt.$$

This must equal the combined work performed by wrenches F_i with velocity V_i at the contact points. We thus have

$$\int_{t_1}^{t_2} V^{\mathrm{T}}F\,dt=\int_{t_1}^{t_2}(V_1^{\mathrm{T}}F_1+V_2^{\mathrm{T}}F_2)\,dt=\int_{t_1}^{t_2}[V_1^{\mathrm{T}}\quad V_2^{\mathrm{T}}]\begin{bmatrix} F_1 \\ F_2 \end{bmatrix}.$$

The integrands must be equal for the integral to hold for any time interval. Making use of the grasp map

$$F=G\begin{bmatrix} F_1 \\ F_2 \end{bmatrix}$$

we obtain

$$V^{\mathrm{T}}G\begin{bmatrix} F_1 \\ F_2 \end{bmatrix}=[V_1^{\mathrm{T}}\quad V_2^{\mathrm{T}}]\begin{bmatrix} F_1 \\ F_2 \end{bmatrix}.$$

Hence, the velocities at the contact points and the object velocity are related through the grasp map as

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix}=G^{\mathrm{T}}V. \tag{2}$$

A special, but common, case is the situation where the two hands grip the same object firmly, and we are only interested in the translation of the object. Then we can exclude the rotational part of Eq. (2). If, further, the translational velocities v, v_1 and v_2 are expressed in the same frame of reference, we get the simpler equation

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}=\begin{bmatrix} I \\ I \end{bmatrix}v=G^{\mathrm{T}}v. \tag{3}$$

2.3. Kinetic energy and co-energy

The distinction between *kinetic energy* and *kinetic complementary energy*, or *kinetic co-energy*, is of interest here, since it highlights the importance of momentum and mobility. Also, we will make use of the different expressions for energy in later derivations.

Velocity V, momentum p, mass M and mobility W are related by the equation

$$p=MV, \tag{4}$$

or, equivalently,

$$V=M^{-1}p=Wp, \tag{5}$$

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