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Enhancing digital human motion planning of assembly tasks through dynamics and optimal control

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Abstract

Better operator ergonomics in assembly plants reduce work related injuries, improve quality, productivity and reduce cost. In this paper we investigate the importance of modeling dynamics when planning for manual assembly operations. We propose modeling the dynamical human motion planning problem using the Discrete Mechanics and Optimal Control (DMOC) method, which makes it possible to optimize with respect to very general objectives. First, two industrial cases are simulated using a quasi-static inverse kinematics solver, demonstrating problems where this approach is sufficient. Then, the DMOC-method is used to solve for optimal trajectories of a lifting operation with dynamics. The resulting trajectories are compared to a steady state solution along the same path, indicating the importance of using dynamics.

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1. Introduction

Although the degree of automation is increasing in manufacturing industries, many assembly operations are performed manually. To avoid injuries and to reach sustainable production of high quality, comfortable environments for the operators are vital, see [1] and [2]. Poor station layouts, poor product designs or badly chosen assembly sequences are common sources leading to unfavorable poses and motions. To keep costs low, preventive actions should be taken early in a project, raising the need for feasibility and ergonomics studies in virtual environments long before physical prototypes are available.

Today, in the automotive industries, such studies are conducted to some extent. The full potential, however, is far from reached due to limited software support in terms of capability for realistic pose prediction, motion generation and collision avoidance. As a consequence, ergonomics studies are time consuming and are mostly done for static poses, not for full assembly motions. Furthermore, these ergonomic studies, even though performed by a small group of highly specialized simulation engineers, show low reproducibility within the group [3].

To describe operations and facilitate motion generation, it is common to equip the manikin with coordinate frames attached to end-effectors like hands and feet. The inverse kinematic problem is to find joint values such that the position and orientation of hands and feet matches certain target frames. For the quasi-static inverse kinematics this leads to an underdetermined system of equations since the number of joints exceeds the end-effectors constraints. Due to this redundancy there exist a set of solutions, allowing us to consider ergonomics aspects, collision avoidance, and maximizing comfort when choosing one solution.

The dynamic motion planning problem is stated as an optimal control problem, which we discretize using discrete mechanics. This results in an optimization problem, which can be solved using standard nonlinear programming solvers. Furthermore, this general problem formulation makes it fairly easy to include very general constraints and objectives.

In this paper we show, using a couple of case studies, where the quasi-static solver is sufficient, and where the DMOC solver could improve the solution. The paper extends the work presented in [4] and [5], and is a part of Cromm (Creation of Muscle Manikins) project [6].

2. Background

2.1. Manikin Model

In this section we present the manikin model and the inverse kinematic problems, both quasi-static and with dynamics.

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2.2. Kinematics

The manikin model is a tree of rigid bodies connected by joints. Each body has a fixed reference frame and we describe its position relative to its parent body by a rigid transformation $T(\boldsymbol{q})$, where $\boldsymbol{q}$ is the coordinate of the joint. To position the manikin in space, i.e. with respect to some global coordinate system, it has an exterior root as the origin and a prismatic joint and a rotation joint as exterior joints as opposed to the interior links representing the manikin itself, see [4]. Together, the exterior links mimic a rigid transformation that completely specifies the position of the lower lumbar. In turn, the lower lumbar represents an interior root, i.e. it is the ancestor of all interior joints. Note that the choice of the lower lumbar is not critical. In principal, any link could be the interior root, and the point is that the same root can be used though a complete simulation. No re-rooting or change of tree hierarchy will be needed. Now, for a given configuration of each joint, collected in the joint vector $\boldsymbol{q} = [\boldsymbol{q}_1^T, \ldots, \boldsymbol{q}_n^T]^T$, we can calculate all the relative transformations $T_1, , T_n$, traverse the tree beginning at the root and propagate the transformations to get the global position of each body. We say that the manikin is placed in a pose, and the mapping from a joint vector into a pose is called forward kinematics. Furthermore, a continuous mapping $\boldsymbol{q}(t)$, where $t \in \mathbb{R}$, is called a motion, or a trajectory of the system.

2.3. Quasi Static Inverse Kinematics

In order to facilitate the generation of realistic poses that also fulfill some desired rules we add a number of constraints on the joint vector. These kinematic constraints can for example restrict the position of certain links, either relative to other links or with respect to the global coordinate system or ensure the manikin is kept in balance, see section 2.3.2. All the kinematic constraints can be defined by a vector valued function $\boldsymbol{g}$ such that

$$\boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{0} \tag{1}$$

must be satisfied at any pose. Finding a solution to equation 1 is generally referred to as inverse kinematics. Often, in practice, the number of constraints is far less than the number of joints of the manikin. Due to this redundancy there exist many solutions, allowing us to consider ergonomics aspects and maximizing comfort when choosing solution. To do so, we introduce a scalar comfort function

$$h(\boldsymbol{q}) \tag{2}$$

capturing as many ergonomic aspects as desired. The purpose is to be able to compare different poses in order to find solutions that maximize comfort. The comfort function is a generic way to give preference to certain poses while avoiding others. Typically h considers joint limits, distance to surrounding geometry in order to avoid collision, magnitude of contact forces, forces and torques on joints, see section 2.3.3. Furthermore, by combining equation 1 and 2 we can formulate the inverse kinematic problem as

$$\max_{\boldsymbol{q}} h(\boldsymbol{q}) \quad \text{subject to} \quad \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{0}. \tag{3}$$

2.3.1. Collision Avoidance

While some contact with the environment may be intended, e.g. grasping of objects and leaning, and contribute to the force and moment balance. Other contacts, for example, collisions, are undesired. The comfort function offers a convenient way to include a simple, yet powerful, method penalizing poses close to collision. In robotics this method is generally known as Repulsive Potential [7][8]. The underlying idea is to define a barrier, say, around the obstacles increasing the discomfort towards infinity near collision. This method does not address the problem of escaping an already occurring collision. The idea is merely that if the manikin starts in a collision-free pose, then the repulsive potential prevents the manikin from entering a colliding pose.

Note: It is common to think of the repulsive potential or rather its gradient field as a force field pushing an object away from obstacles. In this work, we do not want such artificial forces to contribute to the force balance. To avoid confusion with real contact forces we will not use that analogy.

2.3.2. Balance and Contact Forces

One important part of $\boldsymbol{g}$ is ensuring that the manikin is kept in balance. For this, the weight of links and objects being carried, as well as external forces and torques due to contact with the floor or other objects, must be considered. The sum of all forces and torques are

$$\boldsymbol{g}_{force}(\boldsymbol{q}) = m\boldsymbol{g} + \sum_{j \in J} \boldsymbol{f}_i,$$
$$\boldsymbol{g}_{torque}(\boldsymbol{q}) = \boldsymbol{m}_c \times m\boldsymbol{g} + \sum_{j \in J} \boldsymbol{p}_j \times \boldsymbol{f}_j + \boldsymbol{\tau}_j,$$

where m is the total body mass, $\boldsymbol{g}$ is the gravity vector, $\boldsymbol{m}_c$ is the center of mass, $\boldsymbol{f}_j$ and $\boldsymbol{\tau}_j$ are external force and torque vectors at point $\boldsymbol{p}_j$ and J is the index set. Note that the quantities may depend on the pose, but this has been omitted for clarity. In general, external forces and torques due to contacts are unknown. For example, when standing with both feet on the floor it is not obvious how the contact forces are distributed between the feet. In what follows we let $\boldsymbol{f}$ and $\boldsymbol{t}$ denote the unknown forces and torques, and we stack them into the vector $x = [\boldsymbol{q}^T \; \boldsymbol{f}^T \; \boldsymbol{\tau}^T]^T$. Then we can rephrase (3) as follows:

$$\max_{\boldsymbol{x}} h(\boldsymbol{x}) \quad \text{subject to} \quad \boldsymbol{g}(\boldsymbol{x}) = \boldsymbol{0}. \tag{4}$$

2.3.3. Joint Torque

The joint loads are key ingredients when evaluating poses from an ergonomic perspective [9]. Furthermore, research shows that real humans tend to minimize the muscle strain, i.e. minimize the proportion of load compared to the maximum possible load [10], so by normalizing the load on each joint by the muscle strength good results can be achieved. In this article we choose the function

$$h_t = \sum_{i=1}^{n} w_i^2 \boldsymbol{\tau}_i^2$$

where $\boldsymbol{\tau}_i$ is the torque in joint i, and w_i is the reciprocal of the joint strength. Note that it is straightforward to propagate the external forces and torques and the accumulated link masses trough the manikin in order to calculate the load on each joint.