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Digital Human Motion Planning of Operation Sequences Using Optimal Control of Hybrid Systems

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Abstract. In IPS-IMMA the operation sequence planning tool offers an easy and powerful way to construct, analyze, and simulate sequences of human operations. So far, the simulations created using this tool have been quasi-static solutions to the operation sequence. In this paper we present new functionality for motion planning of digital human operation sequences which also takes the dynamics of the human into consideration. The new functionality is based discrete mechanics and optimal control and will be seamlessly integrated into to the IPS-IMMA software through the operation sequence planning tool. First, the user constructs an operation sequence using the operation sequence planning tool in IPS-IMMA. The operation sequence is then converted into a discrete optimal control problem which is solved using a nonlinear programming solver. Finally, the solution can be played back and analyzed in the graphical interface of IPS-IMMA. In order to obtain physically correct solutions to complex sequences consisting of several consecutive and dependent operations, we view the digital human as a hybrid system, i.e. a system containing both continuous and discrete dynamic behavior. In particular, the optimal control problem is divided into multiple continuous phases, connected by discrete events. The variational integrators used in discrete mechanics are particularly well suited for modelling the dynamics of constrained mechanical systems, which is almost always the case when considering complex human models interacting with the environment. To demonstrate the workflow, we model and solve an industrial case where the dynamics of the system plays an important part in the solution.

Keywords. Optimal Control, Discrete Mechanics, Human Motion Planning

1. Introduction

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 [1].

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Traditionally, human simulation tools use these static poses to emulate motion, which severely limits the possible set of motions which can be produced. Our goal is to extend the model in IMMA to be able to generate dynamically feasible motions for the manikin based on a performance index, which could typically include quantities such as comfort, muscle strain, and cycle time. Furthermore, we want to be able to realistically simulate highly dynamic motions, where modelling of inertial effects become crucial. To do this, we model the manikin as a dynamical system, and use optimal control methods to compute the motions. Optimal control is the problem of determining a control function for a dynamical system in order to minimize a given performance index. In order to solve the optimal control problem on a computer, we discretize the continuous problem into a nonlinear programming problem using discrete mechanics. The idea of using optimal control to generate human motion is not new, see for example [2],[3],[4],[5].

In this paper we work with the DHM tool IMMA [6] and show how to generate motions for complex operation sequences using hybrid optimal control techniques. The paper builds on the work presented in [7],[8],[9], and is a part of the VIVA (Virtual Vehicle Assembler) project.

2. Method

Here we briefly describe the kinematical model of the manikin in the DHM tool IMMA. We also describe how we introduce dynamics and optimal control in the model. In this paper we control the manikin by directly applying torques in the joint.

2.1. 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 $T(q)$, where q is the coordinate of the joint. To position the manikin in space, with respect to some global coordinate system, it has an exterior joint positioning the manikin relative to a fixed inertial frame – as opposed to the interior links representing the manikin itself, see (1).

The exterior joint is modeled as a rigid transformation that completely specifies the position of the lower lumbar in the world. 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 can be the interior root, and the point is that the same root can be used through a complete simulation. No re-rooting or change of tree hierarchy is needed.

For a given configuration of each joint, collected in the joint vector q, we can calculate all the relative transformations by traversing the tree, beginning at the root and propagating 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 $q(t)$, where $t \in R$, is called a motion, or a trajectory of the system.

2.2. Dynamics and optimal control

The dynamic motion planning problem is stated as the following optimal control problem:

Minimize

$$\chi\left(\boldsymbol{q}(t_f), \dot{\boldsymbol{q}}(t_f)\right) + \int_{t_0}^{t_f} \mathcal{L}\left(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t), \boldsymbol{u}(t)\right) dt \quad (1)$$

subject to

$$\frac{\partial L}{\partial \boldsymbol{q}}\left(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\right) - \frac{d}{dt}\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\left(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\right) + \boldsymbol{F}\left(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t), \boldsymbol{u}(t)\right) + \boldsymbol{\Phi}^{\boldsymbol{T}}\left(\boldsymbol{q}(t)\right)\boldsymbol{\lambda}(t) = \boldsymbol{0}, \quad (2)$$

$$\boldsymbol{\phi}\left(\boldsymbol{q}(t)\right) = \boldsymbol{0}, \quad (3)$$

$$\boldsymbol{g}\left(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t), \boldsymbol{u}(t)\right) \geq \boldsymbol{0}, \quad (4)$$

$$\boldsymbol{\psi_0}\left(\boldsymbol{q}(t_0), \dot{\boldsymbol{q}}(t_0)\right) = \boldsymbol{0}, \quad (5)$$

$$\boldsymbol{\psi_f}\left(\boldsymbol{q}(t_f), \dot{\boldsymbol{q}}(t_f)\right) = \boldsymbol{0}, \quad (6)$$

for $\mathrm{t} \in [\mathrm{t}_0, \mathrm{t}_\mathrm{f}]$.

Thus, we want to minimize the performance index (1), consisting of the terminal cost, χ, and the integral of the control Lagrangian, $\mathcal{L}$, along the trajectory, while satisfying the dynamics (2)-(3), path constraints (4), and boundary conditions (5)-(6).

The optimal control problem is then discretized. This results in a nonlinear constrained optimization problem, which can be solved using standard nonlinear programming solvers. Furthermore, this general problem formulation makes it straight forward to include very general constraints and objectives. The differential equation in the optimal control problem is discretized using discrete mechanics. In discrete mechanics, the variational principle is directly discretized into a set of nonlinear equations known as the discrete Euler-Lagrange equations. The discrete equations of motions derived in this way have been shown to be superior compared to standard discretizations since they preserve characteristics of the continuous system such as conservation of momentum and a good energy behavior [10]. This results in very stable integrators, which in practice allows us to use large time steps when solving our problems.

In order to efficiently use the discrete equations for these potentially high dimensional systems in a direct optimal control method, it is important to exploit both the structure of the optimal control problem as well as the structure of the dynamics [7].

3. Results

3.1. Hybrid optimal control and operation sequence planning

In this section we use the operation sequence planning tool in IMMA to create an optimal control problem for a given operation sequence. We will use the task of climbing a loader to illustrate the process (Figure 1). Foot attachment points are created at the ground and the steps of the loader. We also put attachment point for the left hand on the rail of the loader. Currently, the placement of the attachment points must be chosen by the user, but functionality to let, for example the attachment point for the hand, grab anywhere on a line segment representing the rail, is in the works.

We are now ready to create our operation sequence. We attach the manikin to the foot attachment points on the ground, and choose this as the start configuration (Figure 1). Operations are then added to the sequence according to Table 1.

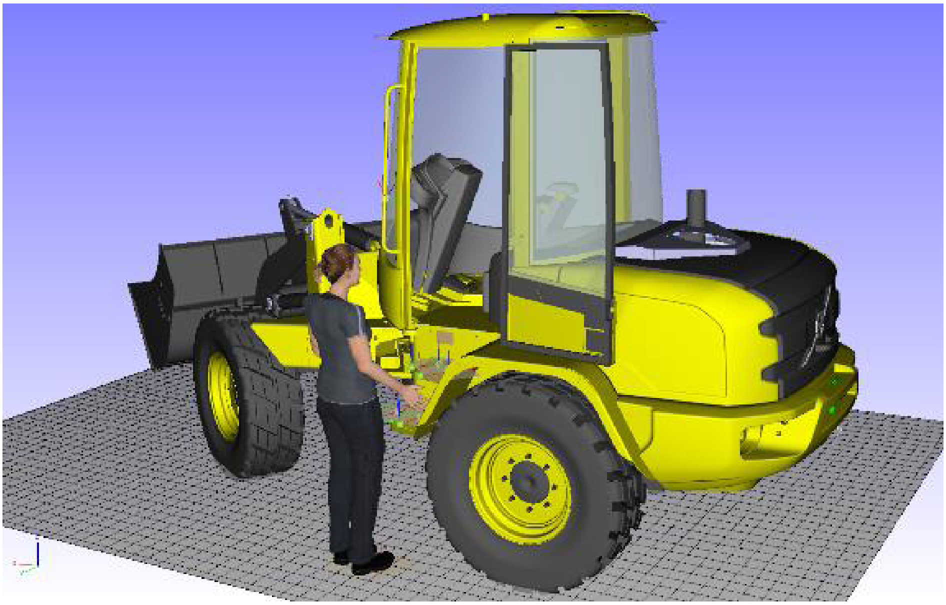

Figure 1. IPS scene.

Table 1. Operations with the resulting duration for each operation. The duration of each operation is determined by the solution to the optimal control problem, except for the final pause with is fixed to 1 s.

Operation	Duration [s]
Start	-
Attach left hand to rail	0.515
Detach left foot from ground	-
Attach left foot to first step of the stairs	0.383
Detach right foot from ground	-
Attach right foot to top of the stairs	0.566
Detach left hand from rail	-
Detach left foot from first step of the stairs	-
Attach left foot to top of the stairs	0.301
Pause	1.00

The detach operations are instantaneous, i.e. have no durations, whereas the duration of the attach operations are initialized to 0.5 s but free to be changed during the optimization, i.e. the durations are variables in the optimization problem. The duration for the pause at the end, however, is fixed to 1 s, otherwise the optimization would simply drive the duration to zero since that would introduce zero cost for the operation. Additionally, the manikin is constrained to end the operation sequence in rest.

Note that the optimal control problem includes discrete points in time where the dynamics of the problem changes discontinuously, namely the opening and closing of the contacts, this type of optimal control problem is called a hybrid problem. We approach this by splitting the optimal control problem into several phases and connecting the phases with appropriate boundary constraints. It is, however, important to note that the operation sequence is solved as one optimal control problem, although containing several phases, i.e. the obtained solution is an optimal solution to the complete operation sequence.

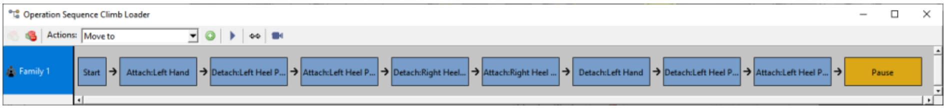

Figure 2. The operation sequence dialog in IPS

Now that our operation sequence is defined **(Figure 2)**, we click the plan-button in the operation sequence dialog **(Figure 2)**. The operation sequence is then converted to a hybrid optimal control problem, which in turn is discretized and solved using a nonlinear programming solver.

The complete operation sequence takes the manikin 2.76 seconds to perform, and can be replayed and analyzed further in IPS **(Figure 3)**.

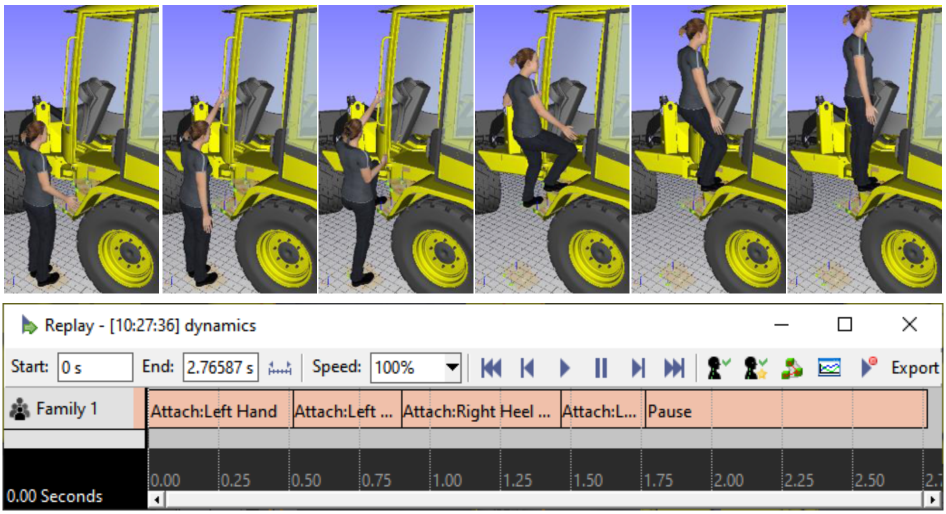

Figure 3. The solution in IPS.

4. Discussion

We conclude that hybrid optimal control is an excellent technique to create dynamic motions from operation sequences created in the operation sequence tool in IPS. Comparing the resulting solution in Section 3.1 to the regular quasi-static solution to the same operation sequence, we see that the dynamics indeed plays an important role in generating a human-like motion. The fact that paths generated by the DHM tool are now dynamic and have a time stamp for each manikin position allows for extended comparisons between simulation results and measures made in the physical world, something we view as one of the great benefits added to the IMMA software.

By modifying the cost functional of the optimal control problem, different motions and behavior can obtained. For example, if more weight is put on completing the operation fast the manikin will use more of its available strength, which results in more aggressive, "athletic", motions.

In this paper we control the manikin by directly applying torques in the joint. However, more advanced control mechanisms, such as muscles and muscle synergies, are possible, see for example [11],[12].

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