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Automatic Creation of Manikin Motions Affected by Cable Forces

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Abstract

Effective simulation of manual assembly operations considering ergonomic load and clearance demands requires detailed modeling of human body kinematics and motions, including balance and response to external forces.
In this paper we address the interaction of humans with flexible objects. By incorporating detailed physics simulation of flexible objects into the creation of ergonomically feasible human motions, we are able to ergonomically assess manual assembly operations involving cables and hoses.
The method is implemented and demonstrated on a challenging operation taken from the automotive industry; a wiring harness assembly.

Keywords: Digital Human Modeling; Inverse Kinematics; Flexible Materials;

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]. 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 [1].

Today, more electrified and hybrid solutions are realized in the vehicles. As a consequence, the amount of cables and hoses that needs to be routed in order to connect the electronic devices has increased. The routing is usually made manually and performed in tight and narrow regions of already compactly designed vehicles. Moreover, the workers also have to consider the shear and strain during the routing of a cable or hose. The shear and strain adds extra forces and torques that an assembly worker needs to consider in order to fully performing an assembly, and may lead to awkward and uncomfortable positions. Thus, there is a need of efficient tools that allows possibility to evaluate the ergonomics of manual assembly operations involving flexible material where the full assembly motion is considered.

Simulations of manikins assembling flexible materials have been presented in [2], in which the digital human Jack [3] was combined with the IPS Cable Simulation software [4]. For each posture of the assembly motion, the force and torque needed in order to hold a cable in a specified position and orientation were transferred to the manikin, which had to repositioning itself in order to resist the forces and torques. In this article we extends the work presented in [5] [6] and take this approach in [2] one step further by letting the manikin change the location and orientation of the cable when it is not completely predefined.

2. Flexible Cables

The simulation of manual assembly operations for ergonomics evaluation is typically done interactively. This way of working puts high performance demands on the software components. When studying the interaction between manikins and flexible objects, the engine for simulation of flexible objects need to be computationally efficient. See [7] for an overview of available methods.

The work presented here is based on the software module IPS Cable Simulation [8]. It is based on Cosserat rods, which are gaining in popularity, and in combination with new mathematical techniques and numerical procedures, reaches real time performance while retaining the necessary physical accuracy [4].

Flexible objects exist in a great variety. In what follows we let *cable* denote any slender flexible object, for example a hose, wire, wiring harness, or rubber sealing.

2.1. Cable Definition

The IPS Cable Simulation module allows quasi-static simulation of virtually any network of elastic cables – anisotropic materials, pre-deformations, arbitrary and varying cross section profiles. The generic input specifying the physical properties of a cable segment is the length density and effective stiffness parameters for bending (in two directions for asymmetric cross section profiles), twisting and stretching.

For a wire or a bundle, the individual strands and fibers are not simulated. Instead, a single cable with aggregated effective material properties is used. This is for example the situation in the test case presented later; the wiring harness is modeled by a number of connected segments, each including the wire bundle and a covering such as tape or a conduit.

For isotropic materials, the effective material properties for elementary cross section profiles like circular, rectangular and elliptic ones (possibly hollow), can be calculated from the density, Young's modulus and the Poisson's ratio.

2.2. Cable Clips

The cable is controlled by specifying boundary conditions, generally called *clips*. A clip can constrain the cable in space by restricting certain degrees of freedom for example fix position, fixed position and orientation, or fixed but with twisting allowed. The last type mimics the behavior of a cable routed through a ring. Furthermore, clips can either be fixed or free relative to arc length position. By connecting multiple clips from separate cable segments into groups that can move freely, any kind of cable branches, joints, and network can be represented [4].

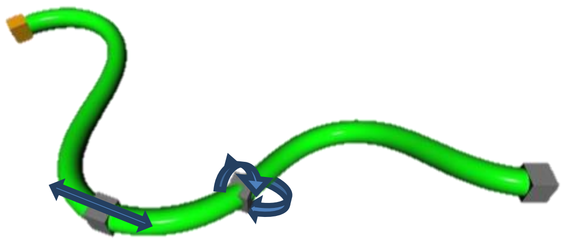

Figure 1: A cable with multiple clips of different types. Both end clips and the left interior clip completely lock the position and orientation of the cable, but the latter one allows the cable to glide through the clip. The right interior clip locks the position, but allows arbitrary rotation.

In our work, we use clips to specify the interaction points between manikins and cables. A manikin can grasp and reposition one or more clips which then in turn will affect the manikin through the torques and forces generated by the cable. A grasp is defined as when the manikins hand is locked into position relative to the clip.

3. Manikin Model

In this section we present the manikin model and the inverse kinematic problem which includes positioning, contact force, collision avoidance, comfort, stability and balance. It will also be described how the cable can directly influence the manikins' postures.

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. 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.

3.1. Kinematics

The manikin model is a simple tree of rigid links connected by joints. Each link has a fixed reference frame and we describe its position relative to its parent link by a rigid transformation $T(\vartheta)$. Here ϑ is the value of the joint between the link and its parent. For simplicity, each joint has one degree of freedom, so a wrist, for example, is composed by a series of joints and links.

To position the manikin in space, i.e. with respect to some global coordinate system, we introduced in [5], an exterior root as the origin and a chain of six additional links denoted exterior links – as opposed to the interior links representing the manikin itself. The six exterior links have three prismatic joints and three revolute joints respectively. 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 links.

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 value for each of the joints, collected in a joint vector $\theta = [\vartheta_1, \dots, \vartheta_n]^T$, we can calculate all the relative transformations $T_1, \dots, T_n$, traverse the tree beginning at the root and propagate the transformations to get the global position of each link. 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 $\theta(t)$, where $t \in [0,1]$, is called a motion.

3.2. 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 4.3. All the kinematic constraints can be defined by a vector valued function g such that

$$g(\theta) = 0 \qquad (4.1)$$

must be satisfied at any pose. Finding a solution to (4.1) 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 one solution. To do so, we introduce a scalar comfort function

$$h(\theta) \qquad (4.2)$$

capturing as many ergonomic aspects as we desire. The purpose is to be able to compare different poses in order to find solutions that maximize the 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 4.4.

Furthermore, by combining (4.1) and (4.2) we can formulate the final inverse kinematic problem as

$$\begin{cases} maximize & h(x) \\ while & g(x) = 0 \end{cases}$$

3.3. Balance and Contact Forces

One important part of g ensures that the manikin is kept in balance. The weight of its links and objects being carried, as well as external forces and torques due to contact with the floor or other obstacles, must be considered. The sum of all forces and torques are

$$g_{force}(\theta) = mg + \sum_{j=1}^{M} f_j$$

$$g_{moment}(\theta) = m_c \times (mg) + \sum_{j=1}^{M} (p_j \times f_j + t_j) \qquad (4.3)$$

where m is the total body mass, g is the gravity vector, m_c is the center of mass, f_j and t_j , are external force and torque vectors at point p_j , $j = 1, \dots, M$. 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 f denote the unknown forces and torques, so the kinematic constraint can be written

$$g(\theta, f) = 0$$

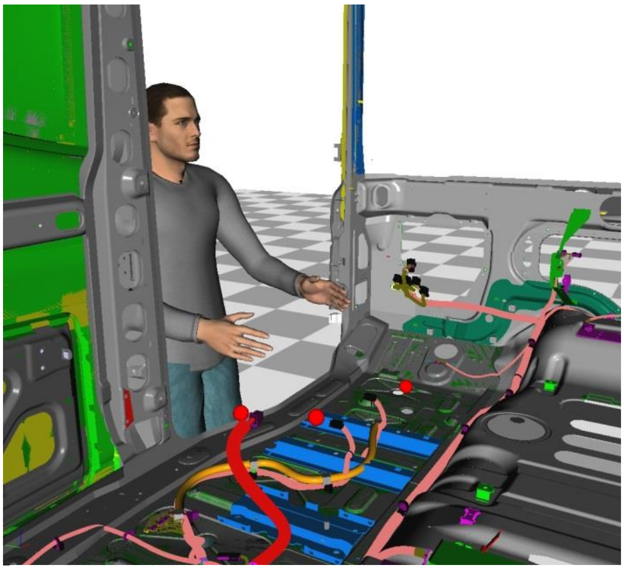

Figure 2: Start posture for the wiring harness assembly.

3.4. 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

$$h_t = \sum_{i=1}^{n} w_i^2 \, t_i^2 \qquad (4.4)$$

where t_i is the torque in joint i, and w_i is the reciprocal of the joint strength.

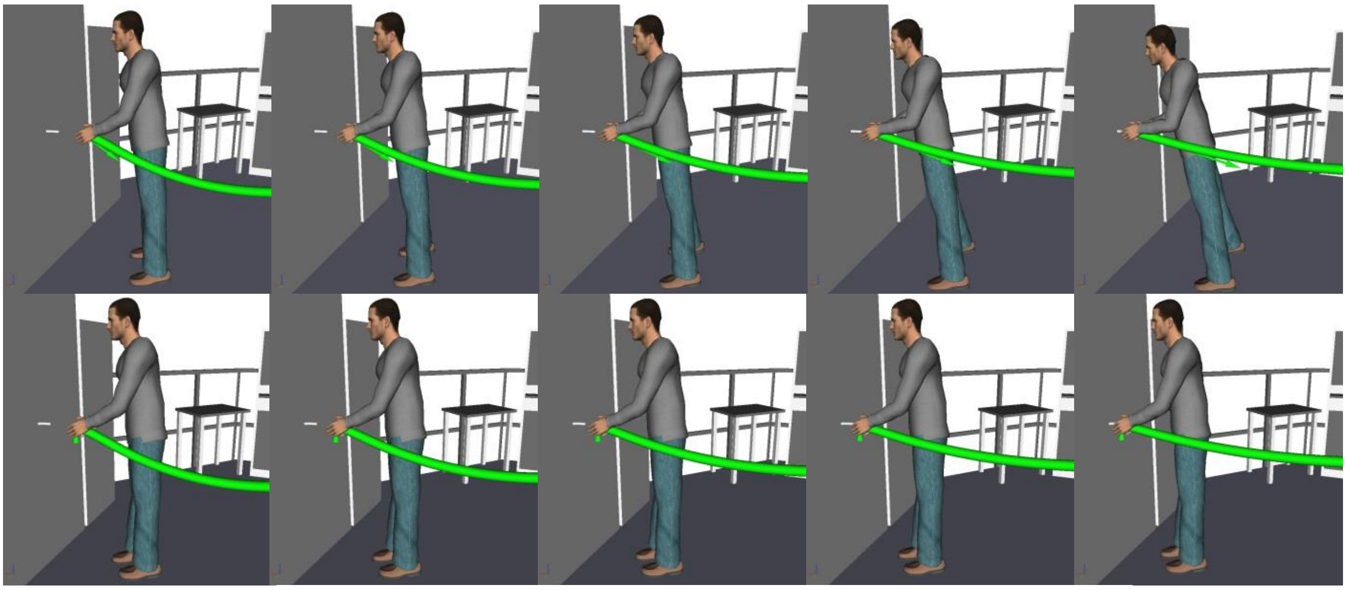

Figure 3: Top row shows snapshots from the hose assembly with cable force feedback while the second row shows without cable force feedback.

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.

3.5. Flexible cables

Here we apply a straight forward technique in order to couple the simulation of the manikin with the simulation of the cables. Via grasps, the manikin controls the position of certain clips. Corresponding forces and moments needed are included as external forces in (4.3), thereby affecting the comfort and the manikin's posture.

The comfort maximization requires the derivative of (4.3) and (4.4). Since the comfort function depends on the position of the cable clips, the derivatives of cable forces and moments with respect to position is required. The forces and moments are continuously differentiable almost everywhere and we calculate the derivatives numerically.

4. Results

In order to demonstrate the applicability of the method used for combining cable forces and torques with the manikin postures, we present two test cases. The first case is artificial with the purpose of distinctly showing the effect of the cable and manikin interaction, and the second case is taken from the automotive industry.

The solutions is generated through specifying the grasping positions, assembly paths guiding the clips and then specifying the work order through the IMMA language, see [11]. In order to allow the manikin to reposition for better balance and ergonomics, the manikin is allowed to slide on the floor and let the clips deviate somewhat from their guiding paths. As the final destination for the clips are approached, the allowed deviation from the guiding paths is reduced.

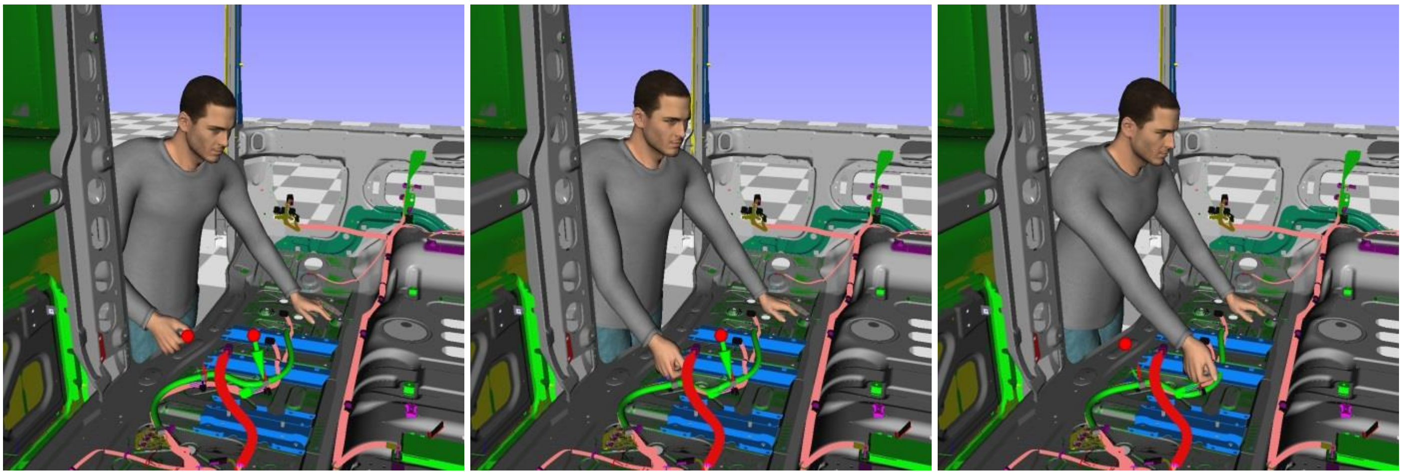

Figure 4: Snapshots from the cable clipping case.

4.1. Hose Assembly

The first case is set up to expose the manikin to large forces and torques through a flexible hose. This is done by letting the manikin lift a hose and connect it to the wall. The manikin grasps the hose with both hands and then pushes it 20 cm into a wall socket. In this case, the cable itself generates all external forces affecting the manikin, i.e., potential friction forces due to the mounting into the wall socket are ignored. The magnitude of the force needed at the final position is 163 N, and because of the straight guiding path, the torque is small. The resulting postures can be seen at the top of Figure 3, and comparable postures without force feedback from the hose can be seen at the bottom. Furthermore, the computation time depends on the magnitude of the resulting force. This comes as no surprise since the coupling between the two systems gets stronger with increasing force and the solver needs more iterations for convergence. Table 1 shows how the magnitude of the force vector at the final position depends on the Young's modulus, E, of the cable material. The calculation time increases accordingly. Without force feedback, the computation time is almost constant – see the right column – reflecting the fact that the engine for simulation of flexible objects is almost independent of the cable's material properties.

E [MPa]	Force [N]	Calc. time with force feedback [s]	Calc. time without force feedback [s]
0.5	62	5.84	5.12
0.7	88	6.19	5.03
0.9	113	6.95	5.16
1.1	138	9.10	5.10
1.3	163	10.71	5.22

Table 1: In the hose assembly case, the calculation time and the magnitude of the force vector at the final position depend on the Young's modulus, E, of the cable material. The right column shows the calculation time without force feedback.

4.2. Wiring Harness Assembly

The second case is to install a wiring harness into position inside a truck; the case is provided by Scania AB. In the real assembly situation, the worker is first to roughly pre-position the wiring harness on the truck floor, and then attach the wiring harness to three clips. Here we only do the second part.

The manikin's start position is outside the door opening with his arms already inside, see Figure 2. Then the manikin uses the left hand as support on the truck floor while doing the clipping. The supporting hand is free to rotate on the surface. In total, the wiring harness shall be attached at three clips.

The effective material properties for the wiring harness are based on measurements of bundles with similar composition. The resulting cable with the aggregated properties is not very stiff and requires forces less than 1 N to be correctly positioned. However, the final part of the assembly motion that snaps the cable into the clips requires an extra force of 50 N.

In Figure 4, snapshots from the resulting motion can be seen. This motion was calculated in about 142 seconds while the same wiring harness clipping without the cable forces took 135 seconds.

5. Discussion

Even though posture prediction is a commonly used term, the goal when simulating assembly motions, and evaluating them from ergonomics perspective, may not be to accurately predict how a human will perform a certain task. Each task may be solved in many ways, and in practice humans tend to vary poses and motion pattern during a day.

Instead, the primary goal in many cases is to prove the existence of at least one feasible motion. Then the human is likely to find one as well, perhaps even a better one. If, however, no feasible motion can be found for the manikin, then actions must be taken. 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.

As can be seen from the two cases presented here, it is now possible to run ergonomic simulations on a wider range of cases because of the coupling between cable forces and manikin postures. In the second test case the computation time was almost unaffected, but in the first case where large forces were present the computation time increased significantly while still being manageable.

Even though many cases can be solved with the current system, there are some cases with extreme cable twisting or unstable energy minima for the cable which are difficult to handle. Unstable configurations exist also for real cables, and designs and assembly motions near such configurations should be avoided. One direction for our future activities concerns analysis inspired by [4] in order to identify and avoid inappropriate designs and motions when being assembled by the manikin.

6. Conclusion

In this paper we address the interaction between humans and flexible objects. By incorporating detailed physics simulation of flexible objects into the creation of ergonomically feasible human motions, we are able to ergonomically assess manual assembly operations involving cables and hoses.

The flexible objects affect the manikin postures through forces and torques due to their deformation and weight. The method is implemented and demonstrated on one artificial hose assembly and one wiring harness assembly from the automotive industry. Both cases where solved successfully with acceptable increase in computation time.

7. Acknowledgement

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