

Progressive Cartesian Inequality Constraints for the Inverse Kinematic Control of Articulated Chains

M. Peinado¹, R. Boulic², B. Le Callennec² and D. Meziat¹

¹ Departamento de Automática, University of Alcalá, Spain

² Ecole Polytechnique Fédérale de Lausanne (EPFL), Virtual Reality Laboratory, Switzerland

Abstract

We propose an Inverse Kinematic Control architecture capable of handling tasks that are expressed in terms of inequality constraints in the Cartesian space. These inequality constraints are progressive in the sense that their influence manifests itself in a zone of finite thickness by damping the progression toward the strict limit of the constraint. We show how to enforce this family of constraints in a two stage process with our prioritized IK scheme. Various examples highlight the potential of this approach for managing complex articulated chains in cluttered environments where obstacles are modelled with this type of constraints.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism---Animation; I.2.9 [Artificial Intelligence]: Robotics

1. Introduction

The present work is motivated by a key problem in the real-time motion control of virtual humans through motion capture. Our long term goal is to provide new interfaces where the end user would specify on the fly the movement of a virtual human in a very intuitive way. One application domain is Virtual Prototyping for which the evaluation of key operations made by potential users of a complex device is currently rather tedious. A constraint-based planning framework has been proposed in [GL02] for a robot arm working in an industrial context. Other efforts exploiting Probabilistic Roadmap have also shown a similar potential for controlling virtual human postures [PLS03,KAA*03]. It could be adapted to the present problem but we favor allowing the user to express the virtual human posture information through their own postures or movements, as in [MB*99]. However this family of motion capture techniques relies heavily on invasive sensors which hinders its adoption outside the Computer Animation field. For this reason we are exploring less invasive approaches where a small number of sensors is used, the key idea being to compensate the missing information through constraints [PHB*04]. We use a Prioritized Inverse Kinematics algorithm similar to [BB04] to enforce the constraints such as gaze, reach and balance (Figure 1). In that context, our experience shows the need for

an automatic management of self-collisions or collisions with the environment, so that the user can focus on the useful part of the task (reachability, maintainance, visibility,...). Our key requirement is to provide a real-time method capable of preventing the collision of a reasonable number of solid primitives (sphere, segment) while enforcing task-oriented constraints with an articulated structure that itself has joint limits. Prior work shows the pertinence of such a strategy [ZB95]. Although we could view the articulated structure as a deformable model and handle its collision detection with a generic approach [GDO00] we prefer to model collision management through *progressive Cartesian inequality constraints* for which we anticipate the collision and alter the hierarchy of prioritized constraints before any hard collision occurs. This approach is inspired by findings in Neuroscience demonstrating the continuity of vision and touch senses; experiments on a monkey have shown that the monkey had a touch sensation when it could see a finger approaching a region of its face, without actually being touched [Ber00]. This clearly suggests to consider the collision within a certain zone around the obstacles *and*, beyond that, to propose an appropriate treatment of the movement within that zone as described in the following sections.

In the remainder of this paper we first discuss the advantages of progressive Cartesian inequality constraints for the collision-free interactive control of complex articulated structures. Then we summarize how to enforce these

constraints using a Prioritized Inverse Kinematic algorithm. Section 4 follows with a brief description of various illustrative case studies. The last section analyses the potential of the method and stresses our future work directions.

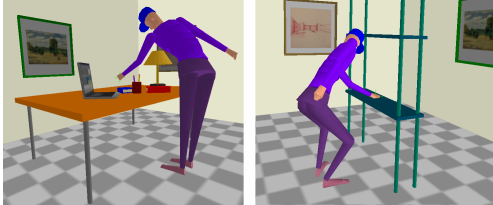


Figure 1: Two reach strategies achieved through Prioritized Inverse Kinematics.

2. Progressive Cartesian Inequality Constraints

Maciejewski and Klein are the first who have exploited the redundancy of an articulated structure for obstacle avoidance [MK85]. Their method pushes away from the obstacle the closest point of the chain within a two priority layers architecture. Khatib introduced the potential field approach to treat the collision avoidance in real-time [Kha85]. We borrow from his approach the approximation through primitives with a finite repulsion zone but we exploit it differently: instead of repulsing any intrusion in the obstacle repulsion zone we only *damp the progression toward the obstacle*. The tangential component of the displacement remains unchanged. This choice is motivated by the observation that it can be legitimate to keep some parts of a complex articulated structure close to other parts or obstacles, as long as they don't move toward each other. This is especially true for human beings for which hands are not repulsed by other body parts. For this reason we name the zone surrounding an obstacle primitive the *smooth collision zone* as movement is only damped when approaching, or entering, the obstacle. Figure 2 illustrate this concept on four points e_1 to e_4 moving with their respective position variations Δe_1 to Δe_4 . The displacement of e_1 is not altered because it always remains outside the collision zone. The displacement of e_4 is also not altered as it moves away from the obstacle. Only e_2 and e_3 see their displacement in the normal direction to the obstacle damped by a uniform viscosity factor.

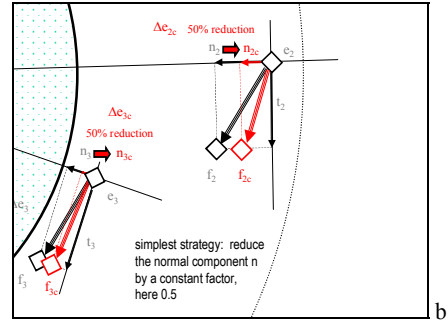
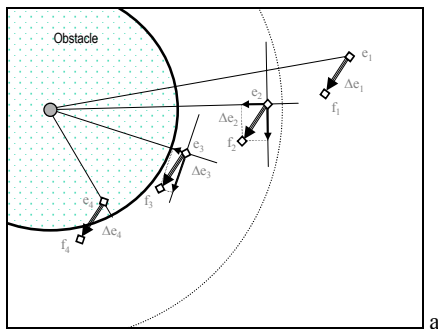


Figure 2: Progression damping in the smooth collision zone of a spherical Cartesian inequality constraint; four moving points e_1 to e_4 (a), only e_2 and e_3 displacements are altered (b).

We have experimented various laws expressing the damping factor, or *viscosity*, as a function of the shortest distance to the obstacle. We have retained the progressive viscosity law illustrated in Figure 3. The viscosity is determined by the distance d from the end point of the displacement to the obstacle, and by the zone thickness D . In the special case where a displacement only partially enters the smooth collision zone, we apply the viscosity only to the fraction of the displacement that belongs to the smooth collision zone. When multiple smooth collision zones overlap, each contributed its correction which is weighted by its viscosity. The resulting normalized vector average is used for the IK control (cf next section).

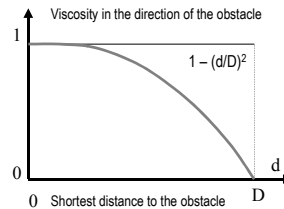


Figure 3: Progressive directional viscosity law.

We are presently using a small set of primitives including sphere, cylinder, line segment, half-plane.

3. Integration in Prioritized Inverse Kinematics

The progressive damping scheme is integrated in our IK framework in two complementary ways:

First the set of regular effectors $\{e_i\}$ associated to goal-oriented position constraints (e.g. reach) are checked against the declared progressive inequality constraints $\{c_k\}$. The desired displacement resulting from each effector constraint $\{\Delta e_i\}$ is adjusted according to the normal damping described in section 2 whenever one or more smooth collisions are detected. In case of hard collision detection, the desired position is pushed on the obstacle surface along the local

repulsive vector. As a result a set of effector constraints with corrected desired displacements and priorities $\{e_i, \Delta e_{ic}, p_i\}$ is provided as the input to the Inverse Kinematics solver (Figure 4a). The output of that component is a posture variation vector $\Delta\theta$ which is now exploited for managing a class of entities called the *observers*.

An observer entity is analogous in type and shape to the primitives used to model the obstacles (e.g. sphere, line segment, cylinder,...). The set of observers $\{obs_i\}$ is distributed on strategic spots of the articulate structure for checking the progressive inequality constraints. For that purpose the displacement induced on them by the solution $\Delta\theta$ is computed. Whenever this displacement Δx_{obs_i} is found to lay inside an obstacle or inside the smooth collision zone of an obstacle, it is corrected (see figure 2) and the colliding observer is temporarily promoted to the status of effector.

This additional set of position effectors $\{obs_{cl}, \Delta x_{obs_{cl}}, p_{cl}\}$ is then added to the current set $\{e_i, \Delta e_{ic}, p_i\}$ which is provided as the input to the Inverse Kinematics solver for re-evaluating the posture variation vector $\Delta\theta$ (Figure 4f). One key issue at that stage is the choice of the relative priorities p_{cl} for this additional set of effectors. There is no doubt about raising the priority of hard colliding effectors above all other effectors' priorities. The choice made for smooth colliding effector tasks is less obvious and subject to experiments. One approach that yields good results is to sort the smooth colliding effector tasks according to their distance to obstacles. Thus, the closer ones get higher priorities keeping the articulated structure safe from future collisions. The results shown in section 4 were obtained with this strategy.

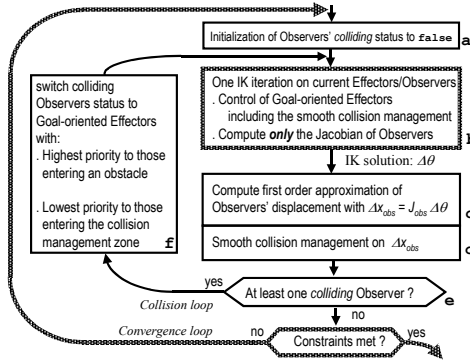


Figure 4: Overview of the enforcement of progressive Cartesian inequality constraints through the observer entities and Prioritized IK.

One last point concerns the computation of the observers' displacements $\{\Delta x_{obs_i}\}$ due to $\Delta\theta$. We can either estimate them by multiplying the observer jacobian J_{obs_i} to $\Delta\theta$ (Figure 4b and c), or we can update a copy of the articulated structure with the state corresponding to the $\Delta\theta$ variation and obtain an exact value. This latter approach is suited for long chains with observers on each segments while the former is more appropriate for complex articulate structures with a small number of observers.

4. Results

4.1. Chain with multiple observers

Here a simple 15 joint chain reaches with its tip a goal located next to its base. A spherical obstacle is placed so close that a severe collision takes place if no collision avoidance strategy is applied (Figure 5a). If only the hard collision part of our algorithm is applied then this collision is prevented, as seen in Figure 5b, but the chain gets arbitrarily close to the obstacle. A better result is achieved by the use of our full algorithm (Figure 5c), in which the prioritized smooth inequality constraints allow to reach the goal while strongly reducing the movement towards the obstacle.

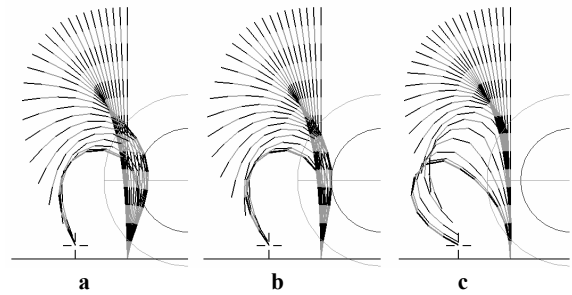


Figure 5: Reaching a goal in presence of an obstacle. (a) No obstacle avoidance. (b) Avoidance of hard collisions only. (c) Smooth inequality constraints added.

4.2. Chain avoiding moving obstacle

In this case study the moving obstacle pushes away the articulated chain while the chain tip is attracted toward its initial position (marked with a cross).

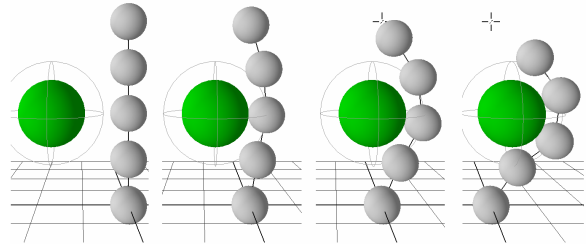


Figure 6: The moving obstacle (big sphere with surrounding smooth collision zone) induces the deformation of the articulated chain.

4.3 Human "pick a book" case study

The experiment proposed here is always surprising when experimented by oneself: just stand up with the back leaning against a wall and the heels also touching the wall, then try to pick an object on the floor: our sense of balance prevents us from achieving this easy task due to the collision with the

wall (Figure 7a shows the picking posture without collision avoidance). We then add three spherical observers and a half plane progressive inequality constraint (Figure 7b). The results as seen in Figure 7c reflect our inability to pick the object due to the relative priorities associated to the different constraints (Table 1).

Using 5 active constraints on an articulated human structure with 22 degrees of freedom, performance on a 2.4 GHz Pentium IV is around 10 ms per update (without graphical display).

Task	Priority Rank
Collision avoidance	1
Keep feet fixed on the ground	2
Center of mass	3
Reach book	4

Table 1: Priority ranking in the “pick a book” case study.

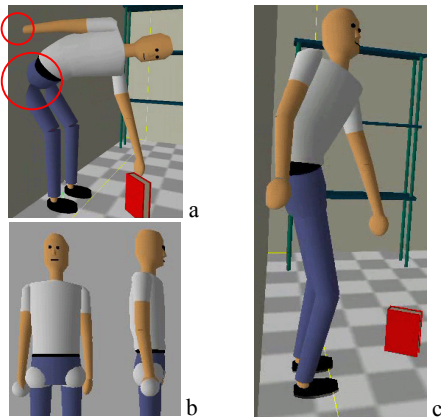


Figure 7: Human “pick a book” case study.

5. Discussion and future work

The progressive Cartesian inequality constraint is an effective concept for the automatic handling of complex articulated chains in cluttered environments even with moving obstacles. The priority mechanism ensures that the goal-oriented tasks are performed first as long as no hard collision is anticipated. The punctual treatment of hard collisions with a temporary higher priority is transparent to the user. Performance is compatible with user interaction. As a consequence the user can focus on essential goal-oriented tasks with the guarantee that the performed actions are made in the allowed space. Some actions might not be achievable too due to the lack of space. We are convinced that this technology is an essential component for medical training

(e.g. catheter manipulation) or for virtual human full body postural control in Virtual Prototyping contexts.

6. Acknowledgements

This research was partly supported by the Swiss National Science Foundation under the grant 200020-101464 and by the European Network of Excellence ENACTIVE.

7. References

- [PHB*04] PEINADO, M., HERBELIN, B., WANDERLEY, M., LE CALLENEC, B., BOULIC, R., THALMANN, D., MEZIAT, D., 2004, Towards Configurable Motion Capture with Prioritized Inverse Kinematics, in *Proc. of the Third International Workshop on Virtual Rehabilitation (IVWR'04), Lausanne Sept. 2004*.
- [BB04] BAERLOCHER, P., BOULIC, R., 2004, An Inverse Kinematic Architecture Enforcing an Arbitrary Number of Strict Priority Levels, In *The Visual Computer, Springer Verlag, 20(6)*, pp 402-417
- [Ber00] BERTHOZ A. 2000. The Brain Sense of Movement. Chapter “building coherence”, Section “seeing with the skin” pp 83-86. In *Perspective in Cognitive Neuroscience, Harvard University Press, 2000, ISBN 0-674-80109-1*
- [GDO00] GANOVELLI, F., DINGLIANA, J., O’SULLIVAN, C., 2000, BucketTree: Improving collision detection between deformable objects, In *Spring Conference in Computer Graphics (SCCG2000), Bratislava*, pp 156-163
- [GL02] GARBER, M., LIN, M.C., 2002, Constraint-Based Motion Planning for Virtual Prototyping In *Proc. ACM Symposium on Solid Model and Applications (Poster)*
- [KAA*03] KALLMANN, M., AUBEL, A., ABACI, T., THALMANN, D., 2003, Planning Collision-Free Reaching Motions for Interactive Object Manipulation and Grasping, *Computer Graphics Forum 22(3)* pp 313-322
- [Kha85] KHATIB, O., 1985, Real-Time Obstacle Avoidance for Manipulators and Mobile Robots, In *IEEE International Conference on Robotics and Automation, St. Louis, Missouri*, pp. 500-505.
- [MK85] MACIEJEWSKI A.A., KLEIN, C.A., 1985, Obstacle Avoidance for Kinematically Redundant Manipulators in Dynamically Varying Environments, In *Int'l J. Robotics Research, 4(3)*, pp. 109-117
- [MBR*99] MOLET T., BOULIC R., REZZONICO S., THALMANN, D. 1999, An architecture for immersive evaluation of complex human tasks, In *IEEE Transaction in Robotics and Automation, Special Section on Virtual Reality, Volume 15 (3), ISSN 1042-296X*.
- [PL03] PETTRE, J., LAUMOND J.-P., SIMEON T. 2003. A 2-Stage Locomotion Planner for Digital Actors”. In *Proc. of Eurographics/ACM SIGGRAPH Symposium on Computer Animation, 258-264*.
- [ZB94] ZHAO, X., BADLER N. 1994. Interactive Body Awareness. In *Computer Aided Design, 26(12)*, 861-866.