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Movement control in biologically plausible frames of reference

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Abstract

Biological findings suggest that human movement is encoded in a variety of action-oriented reference frames. In contrast, robotics movement control is mostly formulated in traditional frames of reference, such as the world frame, or a robot-fixed base frame. In this contribution, we will investigate these biological findings and propose a movement control formulation for redundant robots that are equipped with one or several effectors. We will show that describing and controlling movement in action oriented reference frames yields significant advantages, such as higher invariance and generalization capabilities, better movement quality, and a more intuitive understanding. Controlling movement in action oriented reference frames leads to a very natural looking movements, resembling very much the characteristics of human motion.

1 Introduction

Biological findings suggest that human movement is encoded in a variety of action-oriented reference frames. For instance [6, 9] distinguish between egocentric and allocentric reference frames, and give evidence from neuropsychological studies. Egocentric frames are placed relative to the human, and comprise head-, arm-, gaze- and grasp-centered ones. Allocentric frames are represented in environmental coordinates, such as room- or object centered ones. In [12] it is hypothesized that reaching movements are represented in several brain areas that encode body-centered, eye-centered and hand-centered coordinates. This hypothesis is supported by [20] who argue from a robotics perspective.

In contrast, robot movement is mostly controlled in traditional frames of reference, such as the world frame, or a robot-fixed base. A large number of task-level control concepts for redundant robots have been developed so far. Most of them share the concept of splitting the control objective into a task and one or several hierarchical null spaces. This allows to track a primary control objective precisely in a task space, while the null space can be exploited to satisfy a secondary objective. Often, criteria such as joint limit or collision avoidance are projected into such null spaces. A popular method goes back to Liégeois [15] in the 70s. Others have extended this approach towards introducing hierarchical task spaces [2, 1, 7], to deal with collisions, singularities and ill-defined configurations [16, 17, 21] and have formulated criteria to map into the null space of such systems [4]. A comprehensive overview on such approaches is given in [18, 8]. While above mentioned control concepts are kinematic, [14] describes the relationship between end effector accelerations and forces. This framework is extended in [19] to prioritized objectives.

In this contribution, we will investigate biological findings and propose a movement representation for redundant robots that are equipped with one or several effectors. We think that formulating control laws in biologically plausible action-oriented frames of reference yields a number of advantages. Firstly, such representations have a high invariance. This is particularly advantageous when it comes to learning of movements. Further, applying control in suitable frames of reference may increase the generalization capabilities. Third, action-oriented reference frames allow formulating control problems in lower dimensions as classical descriptions, such as 6d end-effector position and orientation controls. Less constraints increase the dimensionality of the redundant null space, which can efficiently be utilized to improve the quality of the movement. Lastly, controlling movement in action oriented reference frames leads to a very natural looking movements, resembling very much the characteristics of human motion. In this paper, we'll first introduce our control model in Section 2. In Section 3 we explain the employed control concept and show how to incorporate action-oriented task descriptors. A set of biologically plausible action-oriented task descriptors is introduced and explained in Section 4. Simulation results of a humanoid robot will underline the characteristics of the proposed concepts.

2 Kinematic Model

In this section, we will derive a flexible task description that can model robot movement with respect to egocentric and allocentric reference frames. The robot's kinematics is described in the form of a tree structure depicted in Figure 1. The individual links are connected by degrees of freedom (joints) or fixed transformations. Further, the tree may also comprise objects from the environment. This allows to derive the inverse kinematics equations not only with respect to a heel or world reference frame, but also to formulate task descriptors accounting for robot-object relations. In the forward kinematics pass, the transformations of all bodies are computed according to the current configuration space vector $\boldsymbol{q}$. The connectivity of the tree is such that the computation can be carried out starting from a root node and descends the branches of the tree. In the inverse kinematics pass, the related Jacobians are computed. Since they only depend on the degrees of freedom that connect the respective body to the root, the connectivity in this direction is the shortest path towards the root node. We employ an efficient algorithm that allows to compute the Jacobians by re-using the results of the forward kinematics pass which is explained in detail in [3].

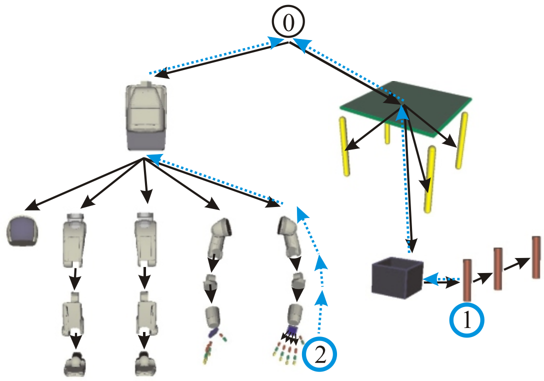

Figure 1: Kinematic tree

In the following, a task descriptor relates the movement of one body with respect to any other belonging to the tree. This allows for instance to describe the position of one end effector with respect to the other, the orientation of the camera to the body, etc.

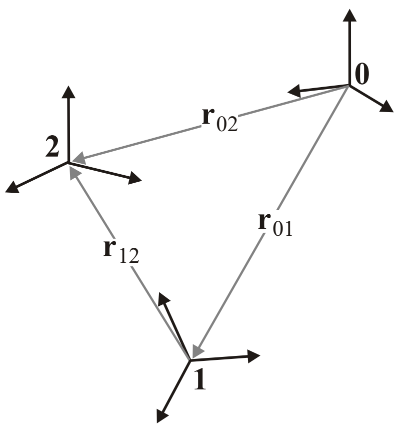

Figure 2: Relative body coordinates

It is also possible to describe robot link transformations with respect to objects in the environment, such as the position of the hand with respect to an object, or the direction of the gaze axis with respect to an object. To mathematically formalize this concept, we look at the relative kinematics of an articulated chain, such as depicted in Figure 2. Coordinate frame 0 denotes its origin. Frame 1 is an arbitrary body which is connected to 0 through a set of joints. Body 2 shall be represented relative to body 1 with vector $\boldsymbol{r}_{12}$. We now can write the (coordinate free) kinematic equations as follows:

$$\boldsymbol{r}_{12} = \boldsymbol{r}_{02} - \boldsymbol{r}_{01} \qquad \dot{\boldsymbol{r}}_{12} = \dot{\boldsymbol{r}}_{02} - \dot{\boldsymbol{r}}_{01} + \boldsymbol{\omega}_1 \times \boldsymbol{r}_{12} \quad . \tag{1}$$

The outer product term of eq. (1) is due to the rotation of body 1. Introducing the coordinate system in which the respective vector is represented as the left sub-index and projecting the velocities into the state space with the respective Jacobians $\dot{\boldsymbol{r}}_i = \boldsymbol{J}_{T,i}\ \dot{\boldsymbol{q}}$ and $\boldsymbol{\omega}_i = \boldsymbol{J}_{R,i}\ \dot{\boldsymbol{q}}$, the differential kinematics gets

$$\begin{aligned} {}_1\dot{\boldsymbol{r}}_{12} &= \boldsymbol{A}_{10}\left({}_0\boldsymbol{J}_{T,2} - {}_0\boldsymbol{J}_{T,1} + {}_0\tilde{\boldsymbol{r}}_{12}^T\ {}_0\boldsymbol{J}_{R,1}\right)\dot{\boldsymbol{q}} \\ &= {}_1\boldsymbol{J}_{T,rel}\ \dot{\boldsymbol{q}} \end{aligned} \tag{2}$$

with $\tilde{\boldsymbol{r}} = (\boldsymbol{r}\times)$ being a skew-symmetric matrix representing the outer product, and $\boldsymbol{A}_{10}$ being a rotation matrix from frame 0 to frame 1. If the reference ("1") body corresponds to a fixed frame, it has no velocity and the corresponding Jacobian is zero. In this case, we get the differential end effector kinematics with respect to an inertial (world-fixed) coordinate system.

The task descriptors for a segments spatial orientation can be computed for instance in Euler (3d) or Spherical angles (2d), or as the inclination of one body axis with respect to any other (1d). It needs to be mentioned that the mapping from a rotation matrix to a serial angle representation is not unique. We therefore compute the differential kinematics in terms of the (unique) angular velocities

$${}_1\boldsymbol{\omega}_{12} = \boldsymbol{A}_{10}\left({}_0\boldsymbol{J}_{R,2} - {}_0\boldsymbol{J}_{R,1}\right)\dot{\boldsymbol{q}} = {}_1\boldsymbol{J}_{R,rel}\ \dot{\boldsymbol{q}}\ . \tag{3}$$

and compute the feedback error $\Delta\boldsymbol{e}$ in eq. (4) with a relative measure, such as the CLIK formulation of [5] for Euler angles, or our formulation [10] for Spherical angles.

With these equations, we can formulate task descriptors that relate any body of the tree to any other. Further, it is possible to compute these descriptors element-wise, such as "position of body 2 with respect to body 1 in x-direction", or "Euler α angle of body 2 with respect to body 0". We also use task descriptors for the linear and angular momentum, or individual joint angles, which are skipped for brevity.

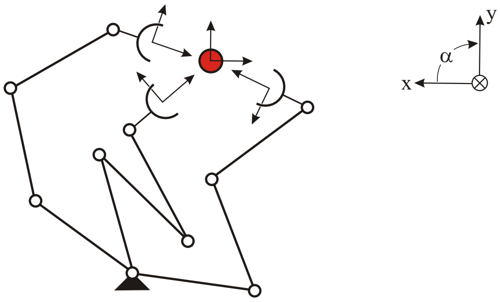

Figure 3: Relative effector - object task description

The choice of the order of the relative coordinates yields some interesting aspects. This is illustrated in Figure 3 for a simple planar redundant system controlled with task variables $(x\ y\ \alpha)$. If the task variables are represented in the objects frame of reference, different values are needed to realize the depicted poses. If, like depicted, the orientation between object and end effector is not important, it may be more advantageous to represent the task variables in the effectors frame of reference. In that case, all three poses can be realized with the same values. This task description introduces an invariance with respect to the relative pose between effector and object. Its null space comprises the relative pose between effector and object. When resolving redundancies, for instance with the scheme described in the next section, the achieved pose will correspond to a (local) optimum with regard to the chosen null space objective.

An important property of this concept is the decoupling from the task description from the absolute or world coordinates. When for instance representing the left end effector's transformation in the frame of reference of the right end effector, the world coordinate trajectories emerge from the secondary objectives in eq. (4). Both end effector's absolute transformations will vary over time according to the secondary objective, while their relative coordinates track the task variables. The absolute coordinates are in that way resolved in the null space of the movement. There are many other examples, such as representing a gazing controller as an object in head-centered coordinates which is "pointed" to by the focal axis, or a pointing controller in a similar way.

3 Whole-body control

To generate the motion, we employ a motion control system that is based on [15]. The task space trajectories are projected into the configuration (joint) space of the system using a weighted generalized pseudo-inverse of the task Jacobian. Redundancies are resolved by mapping the gradient of a joint limit and collision avoidance criterion into the null space of the motion. Details on the whole body control algorithm are given in [10, 11]. The whole body controller is coupled with a walking and balancing controller [13], which stabilizes the motion. Further, a real-time collision avoidance algorithm [21] protects the robot against self-collisions.

Setting up the controller equations is done by augmenting a task Jacobian $\boldsymbol{J}$ holding row-wise the Jacobians of the desired task descriptors that we derived in Section 2. The joint rates are computed as

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{\#}\,\Delta\boldsymbol{e} - \alpha\,\boldsymbol{N}\boldsymbol{W}^{-1}\left(\frac{\partial H}{\partial \boldsymbol{q}}\right)^T \quad . \qquad (4)$$

Matrix $\boldsymbol{J}^{\#}$ is a weighted generalized pseudo-inverse of $\boldsymbol{J}$ with metric $\boldsymbol{W}$ and null space projector $\boldsymbol{N}$:

$$\boldsymbol{J}^{\#} = \boldsymbol{W}^{-1}\boldsymbol{J}^T(\boldsymbol{J}\boldsymbol{W}^{-1}\boldsymbol{J}^T)^{-1} \qquad \boldsymbol{N} = \boldsymbol{E} - \boldsymbol{J}^{\#}\,\boldsymbol{J} \qquad (5)$$

Matrix $\boldsymbol{E}$ is an identity matrix. We chose a diagonal matrix $\boldsymbol{W}$ with elements proportional to the range of the corresponding joint. Vector $\Delta\boldsymbol{e}$ comprises a feedback error term to compensate the tracking error. Scalar H captures joint limit and collision proximities. Its gradient is mapped into the null space with projection matrix $\boldsymbol{N}$ and scalar α defining the step width. We incorporate a joint limit avoidance criterion proposed in [17] which computes as

$$H_{jl}(\boldsymbol{q}) = \frac{1}{2}\sum_{i=1}^{\mathrm{dof}}\left(\frac{q_i - q_{0,i}}{q_{max,i} - q_{min,i}}\right)^2 \quad . \qquad (6)$$

The contributions of each individual joint is normalized with respect to its joint range. To avoid collisions, we use the formulation in [22] and loop through all collision-relevant pairs of bodies, summing up their cost contributions.

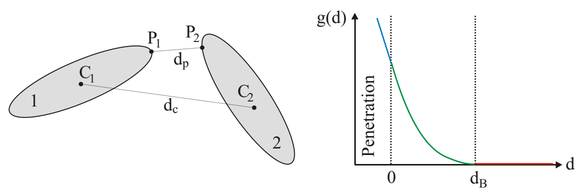

Figure 4: Collision cost function

The cost associated with a pair of bodies is composed of two terms, one related to the distance between the closest points $d_p = |P_1 - P_2|$ and one related to the distance between their centers $d_c = |C_1 - C_2|$, see Figure 4 left. To compute the closest point cost g_p, we set up three zones that are defined by the closest point distance d_p between two collision primitives. Figure 4 right shows the linear, the parabolic and the zero cost zones, respectively. In the region between contact ($d_p = 0$) and a given distance boundary d_B, the closest point cost g_p is determined as a parabolic function, being zero at $d_p = d_B$ and having the slope s for $d_p = 0$. It is progressing linearly for $d_p < 0$, and for $d_p > d_B$, it is zero.

Similarly, the center point cost g_c shall only be active if the link distance has dropped below the distance d_B. The cost function will continuously be scaled with a factor being zero at $d_p = d_B$ and one if $d_p = 0$. This cost adds an

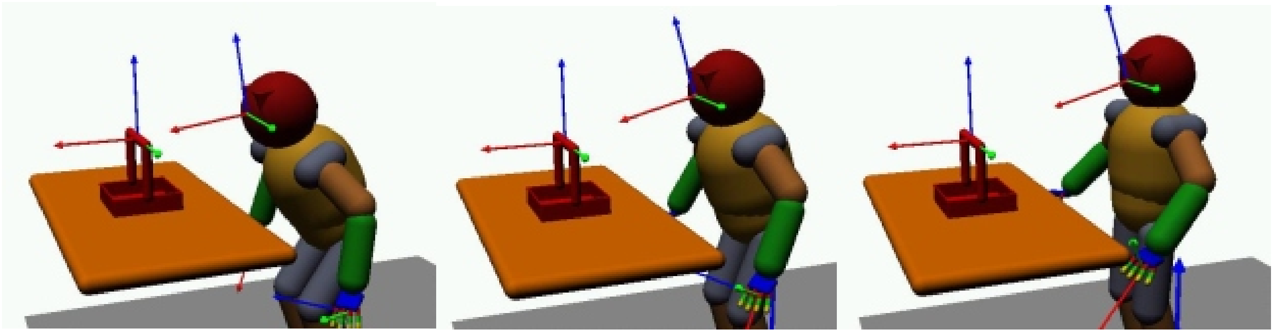

Figure 5: Control in head-centered coordinates.

additional approximate avoidance direction, which is useful when the bodies are in deep penetration and the closest point direction is not well defined. Putting this together, the costs for one body pair become

$$g_p = \begin{cases} s d_B (d_B - 2d_p) & \text{for } d_p < 0 \\ s(d_p - d_B)^2 & \text{for } 0 \le d_p \le d_B \\ 0 & \text{for } d_p > d_B \end{cases} \quad (7)$$

$$g_c = \begin{cases} e^{-d_c} & \text{for } d_p < 0 \\ \left(1 - \frac{d_p}{d_B}\right) e^{-d_c} & \text{for } 0 \le d_p \le d_B \\ 0 & \text{for } d_p > d_B \end{cases} \quad (8)$$

with s defining the inclination of the gradient when penetrating. The overall collision cost is summed over all relevant body pairs as

$$H_{coll}(\boldsymbol{q}) = \sum_i^{pairs} g_p(d_{p,i}) + g_c(d_{p,i}, d_{c,i}) \quad . \quad (9)$$

To derive the overall collision gradient, let us first derive the gradient of the distance $d_p = |p_1 - p_2|$ w.r.t. the joint configuration q. Differentiating with respect to the closest points p_1 and p_2 leads to

$$\frac{\partial d_p}{\partial p_1} = -\frac{1}{d_p}(p_2 - p_1)^T \qquad \frac{\partial d_p}{\partial p_2} = \frac{1}{d_p}(p_2 - p_1)^T \; . \quad (10)$$

If the collidable object is fixed to the environment, the partial derivative of the points with respect to the state is a $3 \times dof$ zero matrix. If it corresponds to a body part or is attached to the robot's body (e.g. held in the end effector), we use the closest point Jacobians $\frac{\partial p_1}{\partial q} = J_{p_1}$ and $\frac{\partial p_2}{\partial q} = J_{p_2}$. With (10) we get

$$\frac{\partial d_p}{\partial q} = \frac{1}{d}(p_2 - p_1)^T (J_{p_2} - J_{p_1}) \; . \quad (11)$$

Analogously we can compute the gradient of $d_c = |C_1 - C_2|$. Differentiating eq. (8) with respect to the distance d_p, and inserting the distance gradient (11) leads to the closest point gradient

$$\left(\frac{\partial g_p}{\partial q}\right)^T = \begin{cases} -2s\frac{d_B}{d_p}(J_{p_2} - J_{p_1})^T (p_2 - p_1) & \text{for } d_p < 0 \\ 0 & \text{for } d_p > d_B \\ 2s\frac{(d_p - d_B)}{d_p}(J_{p_2} - J_{p_1})^T (p_2 - p_1) & \text{else} \end{cases} \quad (12)$$

The cost function g_c depends on the distance of the body centers d_c and on the closest point distance d_p, so we need to apply the chain rule to get the center point gradient:

$$\frac{\partial g_c}{\partial q} = \frac{\partial g_c}{\partial d_c}\frac{\partial d_c}{\partial q} + \frac{\partial g_c}{\partial d_p}\frac{\partial d_p}{\partial q} \quad (13)$$

where

$$\frac{\partial g_c}{\partial d_c} = -\frac{d_B - d_p}{d_B} e^{-d_c} \qquad \frac{\partial g_c}{\partial d_p} = -\frac{1}{d_B} e^{-d_c} \quad (14)$$

and the respective distance gradient is given in eq. (11). The overall collision gradient is

$$\frac{\partial H_{coll}}{\partial \boldsymbol{q}} = \sum_i^{pairs} \frac{\partial g_d(i)}{\partial q} + \frac{\partial g_c(i)}{\partial q}. \quad (15)$$

4 Action-oriented task descriptors

In the following, we will develop different task descriptors and incorporate them into the presented control scheme. We will illustrate the characteristics of the resulting movement using a kinematic model of a humanoid robot as depicted in Figure 5. The model corresponds to the kinematic tree depicted in 1. The upper body is the central body, to which arms, legs and head are connected. The legs have six dof each, the arms are equipped with seven dof. The head's dofs are pan, roll and tilt. Additional to the action-oriented task descriptors that are explained in the following, we control the horizontal components of the overall center of gravity to be in the center of the foot support polygon, and the position and attitude of both feet to be in contact with the ground. The trajectories are generated by applying a linear attractor system to the target values of the selected task descriptors.

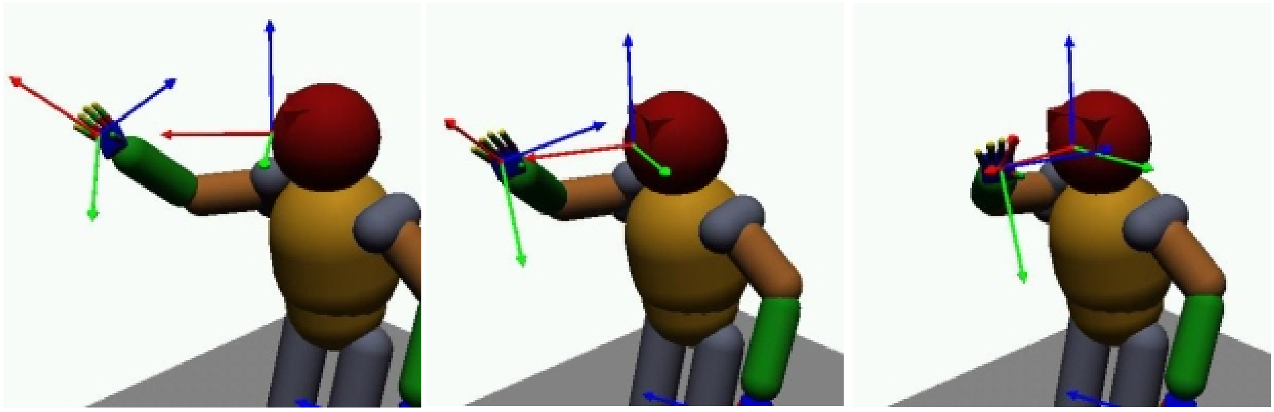

Figure 6: Control in arm-centered coordinates.

4.1 Head-centered representation

This representation is motivated by findings that in humans, there are receptive fields corresponding to the skin surface of the head. We transfer this to our task description by assigning a coordinate frame to the head. This corresponds to the head being body 1, while for instance an object to gaze at is body 2 in Figure 2.
Aligning the gaze axis (tracking) with the object can now simply be done by setting the position components of the object in the plane orthogonal to the gaze direction to $(0\ 0)^T$. Controlling the x-component will affect the distance between head and object along the gaze axis. This is illustrated in Figure 5. The coordinate axes are colored red for the x-, green for the y-, and blue for the z-component. In the middle image, only y- and z-components are controlled to $(0\ 0)^T$, the x-component (distance) results from null space motion. In the left and right images, the x-component is additionally controlled to reduce (left) and increase (right) the head's distance to the object. If the object is moved, the controller will automatically compensate for the shift which results in tracking the object.

4.2 Arm-centered representation

In [6] an arm-centered representation is stated as one attaching the visual receptive field to a part of the skin surface. In the presented model, this can be achieved by controlling a body-fixed point of the arm (surface point, or hand) in the coordinates of the head. Similar to the head-centered representation, the distance (x) component may be uncontrolled, or if desired, be used to control the distance of the eye (or camera) to the point of the arm. This task descriptor can be coupled with others. For instance if the head's pan and tilt angles are controlled, the arm will follow the gaze. Or reversely, if the hand position is controlled, the gaze will automatically follow. This is for instance advantageous for manipulation tasks: They will take place in the operating range of the robot that is most convenient to both gaze at, as well as move the arm and body joints. Figure 6 illustrates this: In the middle image, the hand position is controlled in the heads frame of reference (only the y- and z-components are controlled to $(0\ 0)^T$), which results in the hand frame origin being aligned with the gaze axis. In the left and right image, we coupled this with controlling the task descriptor for the head's pan angle. The hand is moved so that it remains aligned with the gaze axis. It can also be seen that the uncontrolled degree of freedom corresponding to the distance of the hand to the head is utilized.

4.3 Object-centered representation

In the same line of argument, movement can be represented with respect to an objects frame of reference, making the control invariant against relative displacements between robot and object. In our formulation, this comprises the case of objects that are located in the environment, but also the case of bi-manual movements, where objects are a part of the kinematic chain of the robot links. An example would be an object in the left hand that is to be grasped with the right hand. By applying the task kinematics through the coupled kinematic chain of both arms, the problem to grasp an object in one hand with the other hand is consistent with the case of an object that is static in the environment.
While describing the end effector in the reference frame of the object introduces an invariance against the objects absolute transformation, there are cases where it may be advantageous to describe the objects transformation in the reference frame of the end effector. This is depicted in Figure 7. In this example, the robot shall reach towards the target position in the presence of an obstacle. We control the position components as well as the Polar angles of the hand to be aligned with the vertical axis of the target. Further, we projected proximities between hand, fingers and

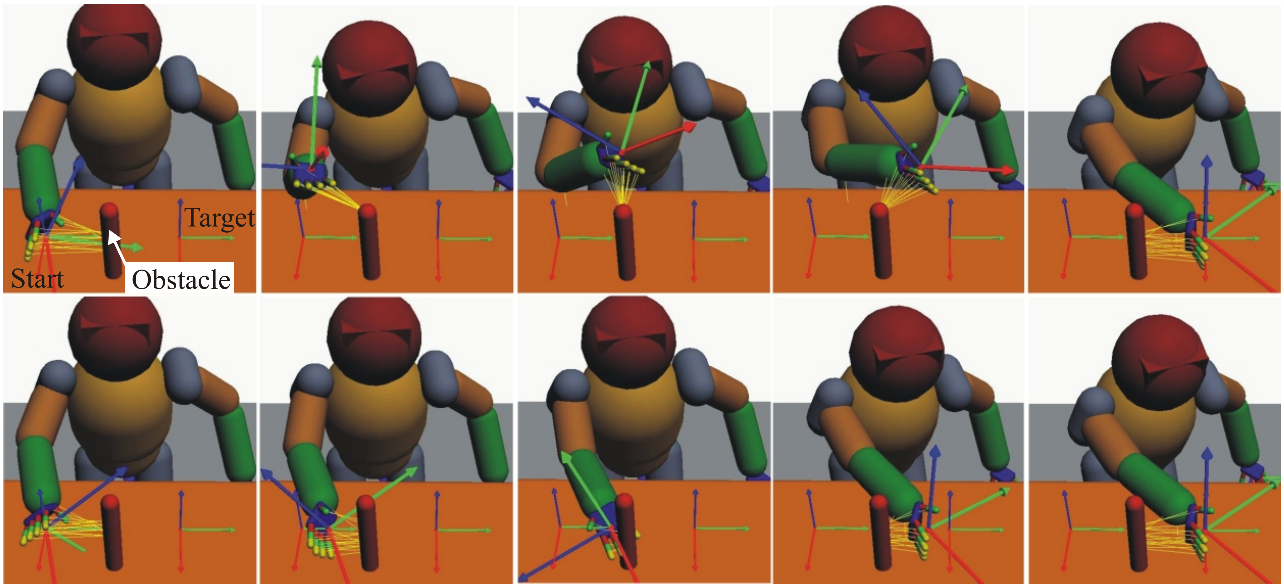

Figure 7: Top row: Control in effector coordinates. Bottom row: Control in object-centered coordinates.

obstacle into the null space of the movement as explained in Section 3. The closest distances are indicated by the yellow lines.

The top row shows the resulting movement when controlling the movement in a hand-fixed reference. Even though the trajectory is linear in the hand's reference frame, the emerging trajectory yields local collision avoidance capabilities, since the world coordinates of the hand are influenced by the null space objective in the same line of argument as given in Figure 3. The bottom row shows the movement controlled with respect to the target reference frame. In this case, the trajectory is linear in Cartesian coordinates and will lead to collisions with the obstacle.

5 Conclusions

In this paper we suggest to describe and control robot movements in biologically plausible action-oriented frames of reference. This yields a number of advantages. Firstly, such representations can have a high invariance. The ranges in which parameters are relevant can significantly be reduced. This is particularly advantageous when it comes to movement learning. Further, applying control in suitable frames of reference may increase the generalization capabilities. Third, action oriented reference frames allow formulating control problems in lower dimensions as classical descriptions, such as 6d end-effector position and orientation controls. Less constraints increase the dimensionality of the redundant null space, which can efficiently be utilized to improve the quality of the movement.

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