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Master Motor Map (MMM) – Framework and Toolkit for Capturing, Representing, and Reproducing Human Motion on Humanoid Robots

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Abstract— **We present an extended version of our work on the design and implementation of a reference model of the human body, the Master Motor Map (MMM) which should serve as a unifying framework for capturing human motions, their representation in standard data structures and formats as well as their reproduction on humanoid robots. The MMM combines the definition of a comprehensive kinematics and dynamics model of the human body with 104 DoF including hands and feet with procedures and tools for unified capturing of human motions. We present online motion converters for the mapping of human and object motions to the MMM model while taking into account subject specific anthropometric data as well as for the mapping of MMM motion to a target robot kinematics. Experimental evaluation of the approach performed on VICON motion recordings demonstrate the benefits of the MMM as an important step towards standardized human motion representation and mapping to humanoid robots.**

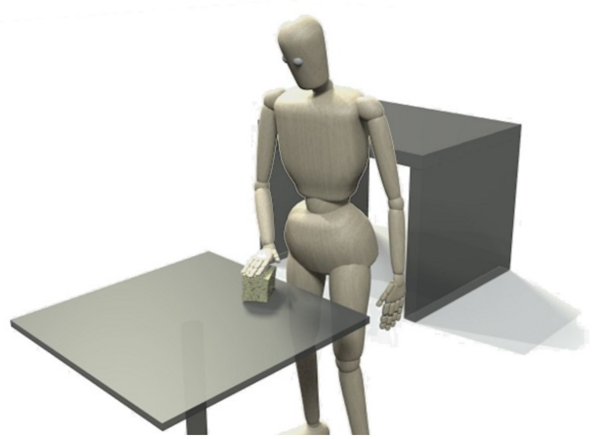

Fig. 1: A ray-traced image of a MMM motion involving an environmental object converted from motion capture data.

I. Introduction

Capturing, understanding and reproducing human motion is a challenging topic in the context of humanoid robotics. A wide variety of different systems and approaches exists, which are used to capture human motion, e.g., visually or by attaching markers to the subjects. Most of these systems are based on their specific data format and model definitions. Furthermore, a large number of approaches for action and activity recognition exists, expecting input data specific to their own internal representation. Finally, any target platform for the reproduction of human motion, e.g., visualization models for animation and simulation purposes and humanoid robots, expects human motion capture data in terms of its own kinematic model.

In order to unify the representation of human motion capture data, we proposed the Master Motor Map (MMM) approach in previous work, see [1] and [2]. With the MMM, it is possible to map and unify different motions coming from varying human motion capture systems to an intermediate MMM model in order to convert these motions in a second step onto different kinematics, such as humanoid robots. This concept has been successfully used for mapping motions originating from different motion capture systems (e.g., from stereo vision or marker-based systems) onto simulated characters and on the ARMAR-III [3] robots. In this work, we present an extended formulation of the Master Motor Map Framework. Besides several improvements regarding modeling, rendering and transparent data specifications, we emphasize how the MMM framework has been extended in order to provide models and data structures for representing manipulation activities (see Fig. 1). Furthermore, we demonstrate how the MMM framework can be used for online reproduction of human motion capture data on humanoid robots. We provide an open source implementation which is available under an open source license[1]. An illustration of the MMM framework is shown in Fig. 2.

The remainder of this paper is organized as follows. Section II gives an overview of the related work in the different aspects covered by this work. The MMM model specifications are described in Section III. Detailed description of the framework and the provided tools and algorithms is given in Section V, Section VI and Section VII. The *Large Scale Human Motion Database* is described in Section VIII while Section IX concludes the work and discusses directions for future work.

II. Related Work

The first introduction to MMM was presented in [1] and proposed an intermediate kinematic model for transferring human motion capture data, which was inspired by [4] and [5] and used a similar kinematic configuration as the human body. The main concept was to use a rigid body system with enough joints, each containing one degree of freedom (DoF), to be able to reproduce any captured human motion.

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[1] http://h2t.anthropomatik.kit.edu/752.php

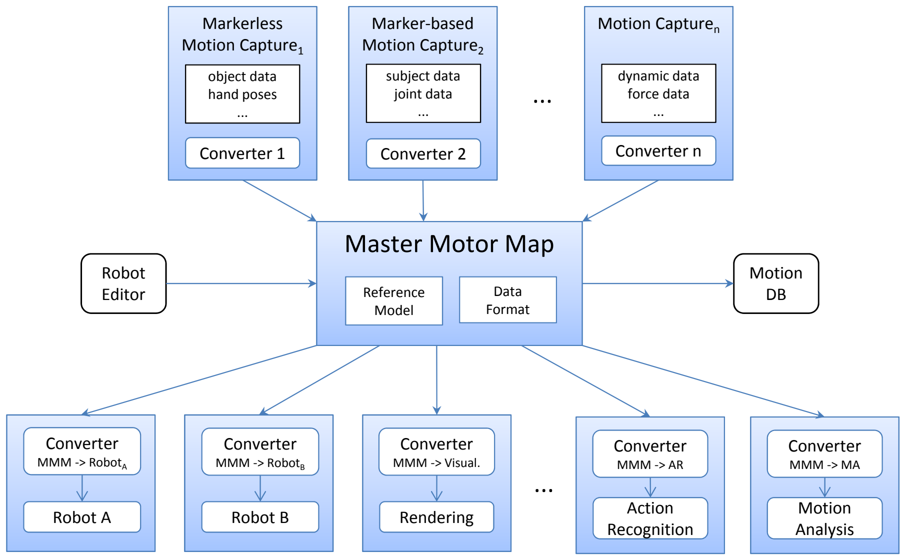

Fig. 2: Illustration of the MMM Framework.

While this has been used mostly for upper body motion reconstruction, lower body kinematic configurations were also provided. This model was later extended in [2] to include dynamic parameters such as the center of mass (CoM), relative weight and radius of rotation for every segment in the body. It also introduced a large-scale non-linear optimization to convert captured motion data to the MMM model and transfer these motions to the ARMAR-III robot [3]. An application to this framework later emerged in [6] which exploited the dynamic properties of the model to extract contact information from human motion capture without any environmental knowledge.

Another approach to determine model properties was taken in [7], where the authors used body scans of 250 subjects to find statistical correlations between body shape variations and subject sizes. Given specific body size parameters, this enabled the authors to give a good estimate about the body shape of the subject. An advanced method to solve the inverse kinematics (IK) using high-order moments of feature points was proposed in [8]. The proposed algorithm enables the computation of the posture of a given model using a wide variety of possible input data. Studies to determine dynamic segment properties of human motion capture were proposed in [9] and [10] where force plate measurement was used to extract the dynamic properties of a subject, such as CoM and mass. Standard parameters form literature were used as starting estimates and interactively refined by providing visual feedback. While some of the obtained results contained physically incorrect estimations, most of them were consistent with literature data. The authors propose a more complete database and additional constraints on the principal moments of inertia to resolve the issue. In [11], a complete overview about animation and control of human simulation is given. This work has a higher focus on interaction in behavior control. Algorithms to reproduce athletic movements in a physically realistic way are presented in [12]. The study tries to find simple but accurate control algorithms for specific sport movements. In this approach different control strategies for different motions are placed in a growing library, where having lots of control strategies for a wide variety of motions is considered to be of high value.

While there are a lot of motion analysis toolboxes like [13] and [14], the most commonly used one is OpenSim [15], a biomechanical framework which focuses on dynamic simulations of musculoskeletal systems and enables the analysis of dynamic properties and muscle activities during different kind of motions. Although this framework is not limited to human models it contains a complete muscularskeletal model of the human body.

III. The MMM Reference Model

We propose the MMM reference model, which consists of a rigid body system with a well defined kinematic configuration and dynamic properties. It is of a normalized size and weight and can be scaled according to subject height and total weight. The kinematic and dynamic specifications of the whole body reference model are based on the biomechanical analysis of Winter et al. [4]. The hand specifications are derived from the analysis of Buchholz et al. as reported in [16] and [17].

A. Kinematic Model

The kinematics of the MMM reference model consists of 104 DoF: 6 DoF cover the model pose, 23 DoF are assigned to each hand, and the remaining 52 DoF are distributed on arms, legs, head, eyes and body.

For convenience, the reference coordinate system in every joint is chosen to have the same orientation when the model

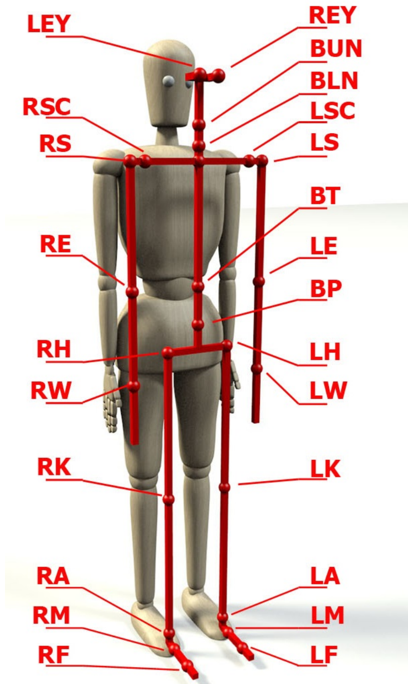

Fig. 3: The kinematics of the MMM reference model.

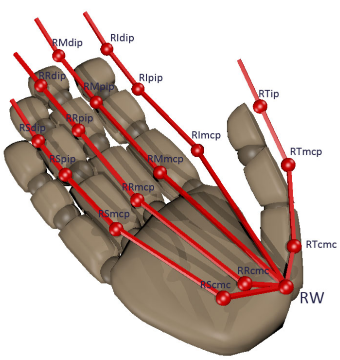

Fig. 4: The kinematics of the right hand.

rests in its initial configuration, that is the x-axis pointing to the right of the body, the y-axis to the front and the z-axis pointing in upwards direction. Also, every multi DoF joint is split into multiple joints with single DoF, where the rotation is first applied about the x-axis, the z-axis and lastly about the y-axis, originating from the base frame, extending to the outer extremities of the model. In order to be able to represent gaze directions, two DoFs are defined for every eye. Further, all joint definitions incorporate a specification of lower and upper limit (see Table I).

The model includes two hands with 23 DoF each (see Fig. 4), where the thumb is modeled with a total of 5 DoF, two at the CMC and MCP joints each and one DoF on the IP joint. The index finger and the middle finger are modeled

TABLE I: Joint configuration details of the reference model.

Joint	DoF	X-Limits	Z-Limits	Y-Limits
LF/RF	1+1	[-30°,45°]	-	-
LM/RM	1+1	-	[-30°,45°]	-
LA/RA	3+3	[-40°,30°]	[-30°, 30°]	[-20°, 20°]
LK/RK	1+1	[-130°,0°]	-	-
LH	3	[-50°,95°]	[-45°,45°]	[-20°,65°]
RH	3	[-50°,95°]	[-45°,45°]	[-65°,20°]
LW	2	[-30°,20°]	[-70°,50°]	-
RW	2	[-30°,20°]	[-50°,70°]	-
LE/RE	2+2	[0°,160°]	[-90°,90°]	-
LS	3	[-70°,190°]	[-70°,60°]	[0°,160°]
RS	3	[-70°,190°]	[-60°,70°]	[-160°,0]
LSC/RSC	2+2	-	[-20°,20°]	[-20°,20°]
LEY/REY	2+2	[-60°,60°]	-	[-60°,60°]
BUN	3	[-20°,30°]	[-20°,20°]	[-15°,15°]
BLN	3	[-45°,15°]	[-15°,15°]	[-20°,20°]
BT	3	[-35°,27°]	[-36°,36°]	[-20°,20°]
BP	3	[-50°,35°]	[-45°,45°]	[-20°,20°]

TABLE II: Normalized segment dimensions with respect to total body height.

Segment Position	δx	δy	δz
BP to BT	0,000	0,000	0,060
BT to LSC/RSC	0,000	0,087	0,188
LSC/RSC to LS/RS	0,023	0,000	0,000
LS/RS to LE/RE	0,000	0,000	0,188
LE/RE to LW/RW	0,000	0,000	0,145
LW/RW to Fingertips	0,000	0,000	0,108
BT to BLN	0,000	0,000	0,210
BLN to BUN	0,000	0,000	0,030
BUN to LEY/REY	0,015	0,030	0,066
BP to LH/RH	0,052	0,000	0,040
LH/RH to LK/RK	0,000	0,000	0,245
LK/RK to LA/RA	0,000	0,000	0,246
LA/RA to LM/RM	0,000	0,020	0,039
LM/RM to LF/RF	0,000	0,048	0,000
LF/RF to Toes	0,000	0,034	0,000

with 4 DoF, where two DoF are located at the MCP joint and one on thee PIP and DIP joints. The ring finger and little finger are extended with an additional DoF at the CMC joint to better enable hand closure.

Literature shows that a three segment foot consisting of hindfoot, forefoot and hallux is sufficient to map human foot motions accurately [18]. We therefore added two additional DoFs to the foot model, which connect the hindfoot with the forefoot and the forefoot with the hallux. For the whole body, without hands, the joints are connected with a total of 25 segments. Detailed anthropometric data is provided in Table II.

It is important to note though, that it is not required to explicitly set every DoF present in the model. For walking motions e.g., finger movements of the hand may be considered unimportant and therefore can be ignored. In this case, the fingers of the hand will just remain in the initial pose.

B. Dynamic Model

Obtaining dynamic properties, such as center of mass (CoM) or the inertia tensor, from living subjects is difficult.

Fig. 5: MMM provides a reference marker set to be used with marker-based human capture systems.

Hence, we rely on reference values from literature which provide statistical analysis and mean values. Some works like [10], where human segment parameters are learned from motion capture and force plate recordings, tend to confirm such literature data. The dynamic properties of the reference model are defined for each segment and include the position of the CoM relative to the segment lengths, the mass of every individual segment relative to the total mass of the subject and the inertia tensor. While the first two parameters can be linearly scaled according to given subject parameters, the inertia tensor has to be recalculated using either the Parallel-Axis Theorem [4] or can be derived from the appropriate radius of gyration values, as described in [2]. In the MMM framework all three parameters are computed according to the given scaling factors.

IV. Human Motion Capture

Although a large variety of human motion capture systems exist, all of them able to be connected to the MMM system, marker-based approaches for capturing human motion data are widely used since they offer the possibility to capture with high accuracy and high framerates. Hence, we propose a reference marker set in order to unify motion recordings and to ease the process of converting them to the MMM format. Note that MMM and, in particular, the MMM converters allow for custom marker placements, if needed. Furthermore, subsets of the reference marker set may be used according to the desired application. In the following, the MMM reference marker set is briefly presented.

A. Whole-Body Marker Set

A reference markerset configuration as depicted in Fig. 5 is proposed. Marker positions are chosen to be placed on specific landmarks of the human body to prevent additional inaccuracies due to skin deformations or muscle movement. Detailed information about the marker positions and names can be freely accessed online[2].

B. Marker Set for Grasping and Manipulation

To allow the observation of human grasping and manipulation actions, the MMM reference marker set contains markers on the human hand which are attached to the fingertips and the palm. Other finger segments have been disregarded in order to minimize the numbers of markers. An illustration of the marker arrangement on the grasping hand is given in Fig. 5.

V. The MMM Framework

A. RobotEditor

For the creation of geometric, kinematic and dynamic models required for the framework as well as the definition of marker sets on the surface of the reference model (or robots, if required by a custom motion converter), the MMM tool chain relies on the *RobotEditor*. This software has initially been developed in the scope of robot hand modeling [19] but has been further developed to support the definition of marker sets on rigid body systems as well as to provide the functionality to define dynamic models, collision models and additional import and export capabilities. With this software, it is possible to easily create kinematic, dynamic and geometric models for rigid body systems such as the MMM reference model, robots and also environmental objects which can directly be used by the MMM toolchain, optionally combined with marker sets for processing motion capture data (see VI-C). The *RobotEditor*[3] is realized as a plugin for the popular open-source 3D content creation suite *Blender*[4] and similar to this software, it is published under an open-source license. Models created with the *RobotEditor* are exported to the industry approved and extendable COLLADA (rev 1.5) file format.The plugin also provides the option for importing motions that have been converted by the MMM framework and/or a custom converter. This allows for high-quality rendered images (see Fig. 1) and videos of the mapped motion for demonstration purposes and preview in the MMM database.

B. MMM Data Format

The XML-based MMM data format consists of two parts. First, setup information is specified, such as converter specific information (e.g., describing specific subject properties) or a specification which subset of the model is used for the following motion data. This allows considering just parts of the reference model, e.g., just the hands in case manipulation activities were recorded. The second part consists of succeeding motion frames where for each frame, basic motion information, such as model position and orientation, is specified. Furthermore joint positions, velocities and accelerations can be defined for each time stamp. In addition, the generic MMM format allows for custom tags which

[2]`https://motion-database.humanoids.kit.edu`
[3]`http://h2t.anthropomatik.kit.edu/748.php`
[4]`http://www.blender.org`

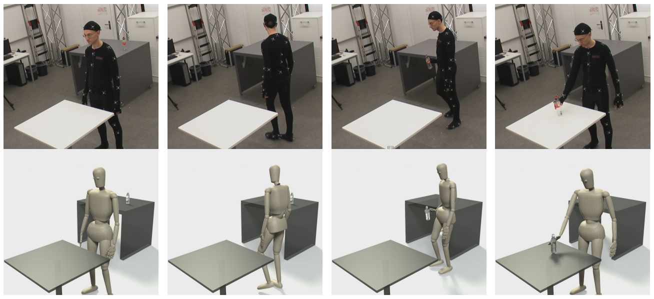

Fig. 6: The top row shows a captured pick and place motion. The converted motions of the reference model and an object are shown below as a ray-traced image sequence.

may cover additional information, such as force values, gaze directions, or symbolic information (e.g., *object grasped*) which may have been generated by a converter.

C. MMM API

The MMM framework provides a platform independent C++ application programming interface (API) which is available under an open source license.The implementation is split into two parts. The first part, the *MMMCore*, contains declaration of key data structures, the MMM model and core functionality like C3D file reading. This lightweight package has a low number of external dependencies to facilitate its use in external projects. The second part, the *MMMTools* project, contains extended algorithms, visualization support and several command line and graphical user interface (GUI) tools. With these tools, the MMM model can be visualized, inspection and playback of motion files and/or marker data is supported, and frontends for converter usage are provided. The generic converter framework of MMM allows for a custom converter implementation, supported by a plug-in system for convenient access.

VI. MMM Converters

MMM Converters are either used to convert human motion capture data to the MMM reference model or for converting motions from MMM to a robot model. With the current API, several reference implementations of converters are provided, which we briefly describe in the following sections.

A. Conversion of Marker-Based Motion Capture Data

For the angle reconstruction, that is, the mapping from recorded marker trajectories of motion capture data onto the reference model, we implemented a basic converter within the MMM framework. In each frame, the approach minimizes the squared distance between recorded marker positions and the virtual markers on the reference model. The Jacobian matrices for each virtual marker position are combined to define an over-determined system of linear equations. Based on the assumption that in between successive frames only a small marker displacement occurs, a nearly linear relation between the Cartesian displacement and the displacement of the joint angles can be assumed and very few iterations are required to find the optimal solution that minimizes the squared error. Additionally, we apply box constraints for respecting joint angle limits based on task-priorities [20] and an active set strategy [21]

$$\Delta\boldsymbol{\theta} = C^{+}\left(\boldsymbol{x}(\boldsymbol{\theta}) - C\cdot\boldsymbol{\theta}\right) + J^{+}(I - C^{+}C)\Delta\boldsymbol{x}(\boldsymbol{\theta}),$$

where

- C denotes a system of linear equations for the fixation for joints at their limits which otherwise would be violated,
- J denotes the combined Jacobian matrix with respect to all marker positions,
- $\boldsymbol{x}(\boldsymbol{\theta})$ the forward kinematics of all marker positions combined into a vector and
- $\Delta\boldsymbol{x}(\boldsymbol{\theta})$ the distances to the real markers given a joint configuration $\boldsymbol{\theta}$ respectively.
- $\Delta\boldsymbol{\theta}$ is the joint displacement that minimizes the squared error.

The model motion depicted in Fig. 6 has been generated with this converter. The complete resulting motion of the reference model is also shown alongside the original human motion in the video attachment.

B. Conversion of Human Hand Movements

The captured fingertip movements (see Section IV-B) are converted into fingertip trajectories in the MMM framework by, first, transforming the movements into a coordinate system located within in the MMM hand. Following the notation of the hand markers in Fig. 5, we defined the origin of this coordinate system to be the marker *RPM* which has been placed on the back of the hand. Using the markers *RHTS* and *RHPS* placed on each side of the hand and *RMFP* which has been attached to middle finger tip, a plane is spanned based on which the axis $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ of the hand coordinate system are calculated as follows:

$$\begin{aligned}\boldsymbol{z} &= \frac{(\boldsymbol{x}_{RPM} - \boldsymbol{x}_{RMFP})}{\|\boldsymbol{x}_{RPM} - \boldsymbol{x}_{RMFP}\|} \\ \boldsymbol{y} &= \boldsymbol{z} \times \frac{(\boldsymbol{x}_{RHPS} - \boldsymbol{x}_{RHTS})}{\|\boldsymbol{x}_{RHPS} - \boldsymbol{x}_{RHTS}\|} \\ \boldsymbol{x} &= \boldsymbol{z} \times \boldsymbol{y}.\end{aligned} \tag{1}$$

Subsequently, the transformed finger positions are scaled according to the ratio $r_H = \frac{l_{H_h}}{l_{H_{mmm}}}$ where l_{H_h} and $l_{H_{mmm}}$ denote the lengths of the observed grasping hand and the MMM hand. Based on anthropometric data which has been reported in [16], $l_{H_{mmm}}$ is defined as a function depending on the global parameters such as full hand height and width. The lengths are measured from the hand's base to the tip of the middle finger.

To obtain a joint angle solution for the MMM hand based on the converted fingertip trajectories, an inverse kinematics (IK) module based on a geometric approach has been implemented. The IK is solved for each finger individually. For the thumb, a plane is spanned based on the target position, mean position of the other fingers, and the position of the CMC joint. Based on the finger segment lengths, a trapezoid with equal inner angles is created which allows us to derive

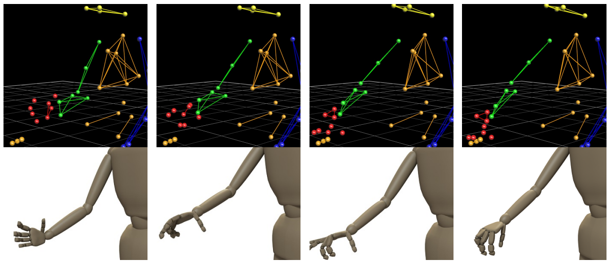

Fig. 7: Mapping of a human demonstration of a tripod grasp captured with the Vicon system. The top line depicts the Vicon motion data; the bottom the mapped MMM hand movements.

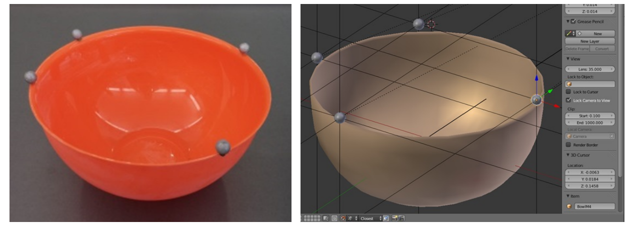

Fig. 8: An object with markers (left) and the modeled instance within the RobotEditor tool (right).

the joint angle solutions for the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint joint. With regard to remaining fingers, based on the projection of the current and the target fingertip positions into the (y, z)-plane the desired joint angle value for the abduction/addiction MCP joint can be easily computed. Similar to the thumb, a plane is created based on the 3D positions of the MCP, the current fingertip, and target position. The resulting trapezoid leads to the flexion joints of the finger. Examples of the mapping procedure of hand movements are depicted in Fig. 7.

C. Converting Object Motions

In order to localize an object from motion capture data, the MMM framework provides the implementation of a converter that obtains the position and orientation of the object using the recorded marker positions and object models that have been enriched by virtual markers using the RobotEditor (see Fig. 8). The converter implements the approach of [22]. In a first step, the centers of the point clouds defined by the real and virtual marker positions are subtracted leaving only the rotation to be reconstructed:

$$\boldsymbol{c}_{\text{Real}} = \frac{1}{N}\sum_{i=1}^{n} \boldsymbol{x}_{\text{Real},i} \qquad \boldsymbol{c}_{\text{Virtual}} = \frac{1}{N}\sum_{i=1}^{n} \boldsymbol{x}_{\text{Virtual},i},$$

given N recorded markers and their positions $\boldsymbol{x}_{\text{Real},i}$ at the actual frame. In the next step, the covariance matrix H of the positions is determined

$$H = \sum_{i=1}^{N} (\boldsymbol{x}_{\text{Real},i} - \boldsymbol{c}_{\text{Real}}) \cdot (\boldsymbol{x}_{\text{Virtual},i} - \boldsymbol{c}_{\text{Virtual}})^T$$

and the rotation matrix R is obtained by the its singular value decomposition (SVD)

$$\begin{aligned}[U, S, V] &= SVD(H)\\ R &= V \cdot U^T.\end{aligned}$$

An exemplary result of this converter can be seen in Fig. 6.

D. Conversion of MMM Movements to Robots

For the mapping of MMM movements to robotic embodiments a generic conversion method has been implemented based on the approach introduced in [23]. The method can be adapted to different robots by specifying an active joint map and the kinematic chains via an XML file. An active joint map denotes the correspondences between the robotic joints, which can be actively actuated, and their equivalents in the MMM model. The conversion of an MMM movement is performed in a two-step procedure. In the first step, an initial joint angle solution is found by aligning the active robotic joints according to the orientations of the corresponding MMM joints. In addition, the target end effector positions encoded in the MMM movements are transformed and scaled according to the robot's global specifications (global coordinate system, total height and width). To retain the goal-directedness of the movement to be mapped, in a second step, an optimization procedure is performed for each kinematic chain in order to find an optimal joint angle solution which is close to the initial solution, but ensures that the robot's end effectors reach the designated target positions. For further details on the optimization procedure, we refer to [23]. Due to the low computational costs and the small number of parameters, the implemented conversion method can be adapted to different robotic embodiments with less effort and allows the mapping of MMM movements onto a robot in an online manner (see Fig. 9).

VII. Online Reproduction of Human Motions

The capabilities of the framework can also be used for instantaneous mapping of human motion capture data onto humanoid robots. The MMM converters are used online for both steps: First, the captured human motions are converted to the MMM reference format for the MMM reference model and second, the MMM motion is reproduced on a humanoid robot. The whole process is performed with 30 frames per second running on a standard Linux PC.

Due to its computational efficiency, the above described conversion approach (see Section VI-A) is well suited for real-time angle reconstruction when performing only a single (or a small number of) optimization steps between subsequent frames. In combination with a real-time capable converter for mapping the reconstructed joint angle trajectories of the reference model to a humanoid robot (see Section VI-D), the toolchain is capable of mapping captured human motion data online to a humanoid robot. To demonstrate this feature we exemplary show an online mapping to the humanoid robot ARMAR-III. We therefore have to access the data stream of a motion capture system and enable a communication between the two converters by using the middleware of the ArmarX robot programming environment [24].

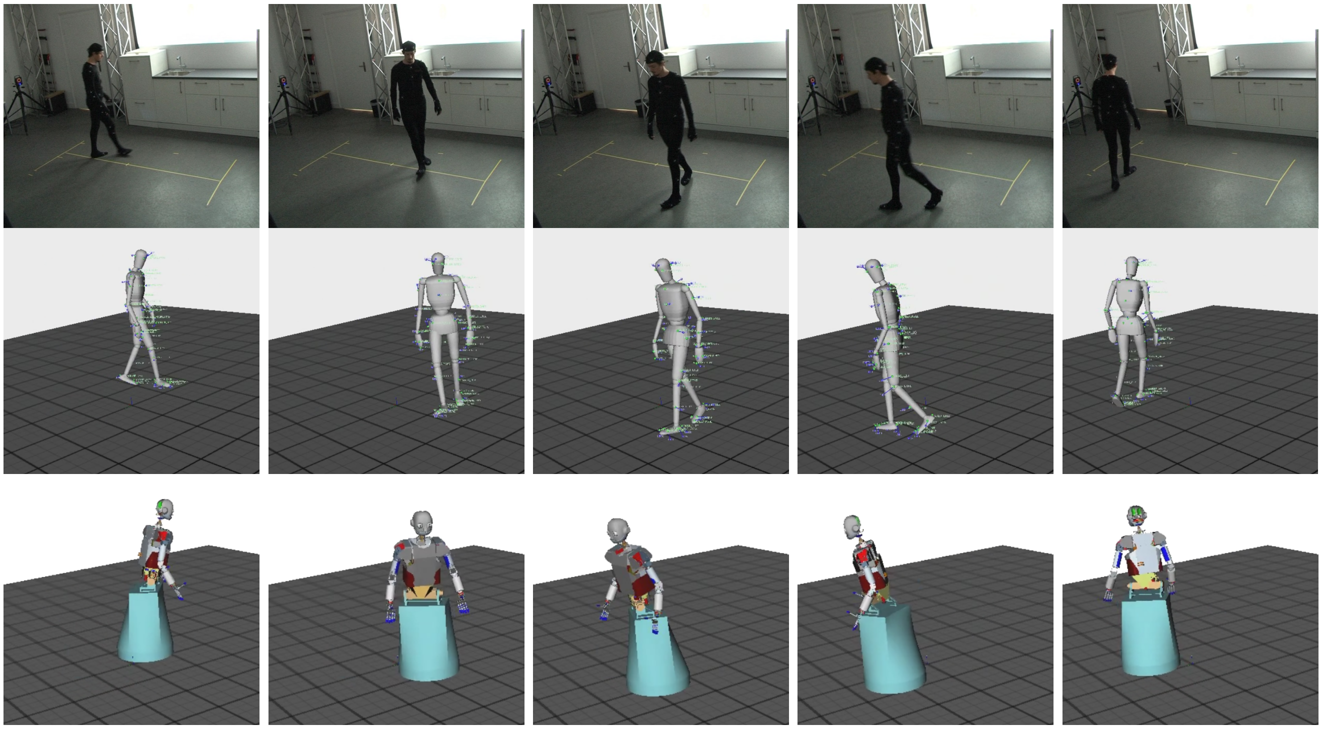

Fig. 9: Online motion conversion in the framework: First, the current motion capture frame (top row) is converted to the MMM reference model (middle row) in order to convert it immediately to the ARMAR-III model (bottom row).

A demonstration of this setup is shown in Fig. 9 and in the attached video.

VIII. Motion Database

The KIT Whole-Body Human Motion Database[5] has been developed as part of the MMM framework to create a comprehensive database of high quality human whole-body motion capture (MoCap) recodings and encourage exchange of MoCap data between different institutions. Existing MoCap databases include the CMU Graphics Lab Motion Capture Database [25], HDM05 [26] and MocapClub.com [27]. Our database differs from existing MoCap databases primarily in its deep integration into the MMM framework, our approach to establish a clean and consistent motion description and in the existence of an application programming interface (API).

Motion recordings in the database are organized into projects which correspond to the source of the respective recording. Subjects and objects which are recorded are entered into the database to collect their anthropometric data and object attributes respectively. Read access to the Motion Database is freely available to everyone without registration, with the exception of some information affected by subjects' personal rights.

A crucial point in the design of large-scale motion databases is the availability of a clear and precise description of the recorded motions. We have devised an extendable tree of motion descriptions that allows a categorization of motions. For example, a motion might be categorized as "locomotion/bipedal/walk/forward", "direction/upwards" and "speed/slow". Data in the database can be filtered on the server side to return only records contained in a certain subtree of the motion description tree. Besides the motion description tree, the database allows filtering records by projects, subjects and objects.

The KIT Whole-Body Human Motion Database can be accessed both via a web interface and an API using the Internet Communications Engine[6] (Ice) as a middleware platform. The Ice-based API facilitates integration of the database into existing tools, e.g., for batch processing of MoCap recordings.

IX. Conclusions

In this work, we presented an extended version of the Master Motor Map (MMM), a framework and toolkit for capturing, representation and reproduction of human motions in the context of humanoid robotics. We introduced a 104 DoF intermediate model of the human body including hands and feet. We showed how the generic converter framework of MMM allows to extract model motions in order to capture and represent interactions of humans with the environment. Finally, we presented the online capabilities of the framework by demonstrating an instantaneous reproduction of human motion capture data onto humanoid robots. The complete MMM tool chain has been demonstrated in the video attachment. In future work, the MMM framework will be the basis for realizing a wide variety of converters covering

[5] `https://motion-database.humanoids.kit.edu`

[6] `http://zeroc.com/ice.html`

challenging domains, such as constrained walking or human-human interaction scenarios.

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