Robot Imitation: A Matter of Body Representation

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***Abstract*— There are two functional elements used by humans to understand and perform actions. These elements are: the body schema and the body percept. The first one is a representation of the body that contains information of the body's capabilities. The body percept is a snapshot of the body and its relation with the environment at a given instant. These elements are believed to interact between them generating among other abilities, i.e. the ability to imitate. This paper presents an approach to robot imitation based on these two functional elements. Our approach is gradually expanded by using four developmental stages of imitation on humans as a guideline.**

***Keywords*—Robot Imitation, Body Representation, Action Representation.**

I. INTRODUCTION

In order to perform an action, lifting a box for example, we require information from our body parts. Imagine that you are standing and wish to pick up a shoe box lying at your feet. You can easily picture yourself bending at the waist and the knees until you can grasp the box with your hands. Once the box is grasped you can straiten back up to standing position. The information that our bodies require to perform an action, like the one above, is frequently divided into: the body schema, which contains the relations of the body parts and its physical constraints. And the body percept, which refers to a particular body position perceived in an instant.

The body schema and the body percept give us an insight into how other people perform certain actions. Since the knowledge of feasible actions and physical constraints is implicit in the body schema, it is possible to do a mental rehearsal of other peoples' actions and gather the results of those actions at particular body percepts for the body schema. The understanding of other people's actions would lead to imitation. The body schema and the body percept give us the insight into recognizing actions and thereby performing these actions. Regarding imitation psychologists present four developmental stages to which the body schema and the body percept contribute.

Imitation, the ability to recognize, learn and copy the actions of others, rises as a very promising alternative solution to the programming of robots. It remains a challenge for roboticists to develop the abilities that a robot needs to perform a task while interacting intelligently with the environment [1], [3]. Traditional approaches to this issue, such as programming and learning strategies, have been demonstrated to be complex, slow and restricted in knowledge.

Learning by Imitation could equip robots with abilities to perform efficient human-robot interaction, eventually helping humans in personal tasks [3]. In addition, imitation presents some desirable characteristics for robotic systems such as *effective learning*, *transfer of implicit knowledge*, and *reduced cost of programming* [4].

The rest of the paper is organized as follows. Section II presents the background theory that has inspired our work on imitation. The next three sections present the first stages of our imitation approach, implementation issues are also offered. Section III discusses the body configuration and its importance for building the body schema. In Section IV, it is described how the interaction between body schema and body percept produces imitation of body movements. Section V gives details of the use of environmental states to achieve imitation of body movements. Experiment results are presented in section VI. Finally, Section VII concludes the paper.

II. FOUNDATION

Humans can perform actions that are feasible with their bodies. The information used by the body in order to carry out an action is derived from two sources:

- *The body schema* is the long-term representation between the spatial relations among body parts and the knowledge about the actions that they can and cannot perform.
- *The body percept* refers to a particular body position perceived in an instant. It is built by instantly merging information from three sources: sensory input, visual input, and proprioception; with the body schema. It is the awareness of a body's position at any given moment.

The information from the body percept is instantly combined with that from the body schema. For instance, by observing someone lifting a box one can easily determine how one would accomplish the same task using one's own body. This means that it is possible to recognize the action that someone else is performing.

The body schema, a body representation with all its abilities and limitations, along with the representation of other objects can simulate any given action, for instance the box lifting example. Imagine that you see someone lifting a box. The body schema allows you to understand what he is doing and how you would go about picking the box up yourself. It is possible then to indicate the main two functions of the body schema:

- *Direct action* is when an action is performed from a current position to produce a new position.
- *Inverse action* is the loop-up for an action that satisfies a goal position from the current one.

The interaction between the body schema and the body percept permits us to understand the relationships between ourselves and other's bodies. Thus, in order to achieve a target perceived action a mental simulation is performed constraining the movements to those that are physically probable.

The body schema provides the basis to understand similar bodies and perform the same actions [15]. This idea is essential in imitation. In order to imitate, it is first necessary identify the observed actions, and then be able to perform those actions. Nevertheless, there are several stages of progression of the imitative abilities. One attempt to explain the development of imitation is given by Meltzoff, who had introduced a four-stage progression of the imitative abilities [20], details of each stage are presented below:

- *Body babbling.* This is the process of learning how specific muscle movements achieve various elementary body configurations. Thus, such movements are learned through an early experimental process, e.g. random trial-and-error learning. Because, both the dynamic patterns of movements and the resulting end-states achieved can be monitored proprioceptively, body babbling can build up a map of movements to end-states. Thus, Body babbling is related to the task of constructing the body schema (the physics of the system and its constrains).
- *Imitation of body movements.* This demonstrates that a specific body part can be identified i.e. organ identification [14]. This supports the idea of an innate observation-execution pathway in humans [7]. The body schema interacts with the body percept to achieve the same movements, once these are identified.
- *Imitation of actions on objects.* The ability to imitate the actions of others on external objects undoubtedly played a crucial role in human evolution. This is done by facilitating the transfer of knowledge of tool use and other important skills from one generation to the next. This also represents flexibility to adapt actions to new contexts.
- *Imitation based on inferring intentions of actions.* This requires the ability to read beyond the perceived behaviour to infer the underlying goals and intentions. This involves visual behaviors and internal mental states (intentions, perceptions, emotions) that underlie, predict, and generate these behaviors.

These four developmental stages serve as a guideline for our progress in research. This paper reports our experiences accomplishing body babbling, imitation of body movements, and imitation of actions on objects with a robotic system.

Roboticists have begun to focus their attention on imitation. Since the capability to obtain new abilities by observation represents many important advantages, imitation intends to fill the gap to *human-robot interaction* [2], [9]. Imitation also seems that it could be a tool to acquire new behaviors and to adapt these within new contexts [4]. Imitation it is also a very promising alternative to way that robots are programmed.

III. BODY CONFIGURATION

Body babbling endows us with the elementary configuration to control our body movements by generating a map. This map contains the relation of all the body parts and their physical limitations. In other words, this map is the body schema.

As humans grow and their bodies change, the body schema is constantly updated by means of the body percept. The body percept, in turn, gathers its information from sensory, visual, and proprioception information. If there is an inconsistency between the body schema and the body percept, then the body schema is updated.

In robotics, since the bodies of robots are changeless in size and weight, body babbling should be very simple. Therefore, instead of letting a robot build its body schema by random trial-and-error learning as humans do, we could simply endow the robot with a control mechanism. That mechanism will permit the robot to know its physical abilities and limitations. In the following sub-section the robotic platform used in our experiments is introduced and its control mechanism is described.

A. The Robot Hardware and Control Mechanisms

The robotic platform used is a mobile robot Pioneer 2-DX with a Pioneer Arm and a camera, namely United4 (Fig. 1). The robot is a small, differential-drive mobile robot intended for indoors. The robot is endowed with the basic components for sensing and navigation in a real-world environment, including battery power, drive motors and wheels, position encoders, and range-finding ultrasonic transducers. These components are managed via microcontroller board and the onboard server software (ActivMedia Robotics Operating System). This operative system has an open API for server-client software control of the robots systems and accessories. The access to the onboard server is through an RS232 serial communication port from a client workstation.

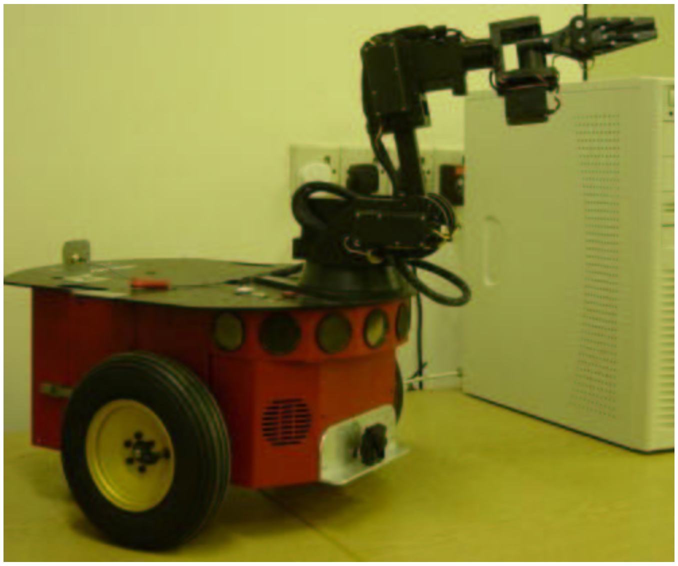


Fig. 1. The robot United4 is the robotic platform we used. It is a Pioneer 2DX with a Pioneer Arm and a camera.

Our robot is also equipped with a vision system and a color tracking system. The vision system consists of one camera placed at the "nose" of the robot, which captures the images to be processed. The color tracking system provides information about the position and size of the colored objects. Color simplifies the detection of the relevant features.

The Pioneer Arm is an accessory for the robot, which is used for robotics in research and the classroom. The robotic arm is five *degrees-of-freedom (DOF)*, the end-effector of which is a gripper with fingers allowing for the grasping and manipulation of objects. The Pioneer Arm can reach up to 50 cm from the center of its base to the tip of its closed fingers.

All the joints of the arm are revolute with a maximum motion range of 180°. To control the arm we use kinematic methods. These methods are dependent on the type of links that compose the robotic arm or manipulator, and more important they are determined by the way they are connected.

United4 is a situated machine, which interact in the real world by changing the values of its effectors. Changing the value of such variables will produce a movement in space and therefore a new position. Therefore, position control mechanism is required, which would allow the robot to know its position in time. The control mechanism described here is for the robotic arm.

The kinematic analysis studies the motion of a body with respect to a reference coordinate system, without considering speed, force or other parameters influencing the motion [13]. A type of this kinematics is the *forward kinematics*. The forward kinematic analysis permits to calculate the position and orientation of the *end-effector, gripper* or *hand* of the robotic arm, when its joint variables have changed.

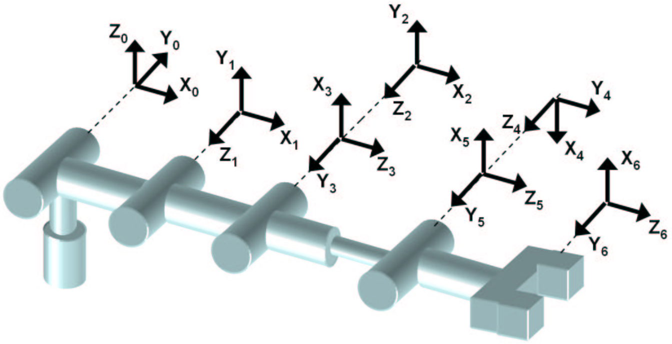


Fig. 2. The assignation of the reference coordinate system for the five DOF pioneer arm.

The Denavit-Hartenberg (DH) convention and methodology were used to derive the Forward Kinematics. The kinematic analysis depends on the robot geometry. In the manipulator both the location and orientation of the hand are defined in terms of the joint variables. Hence, it is necessary obtain the parameters that define the relation among joints. The relation of the coordinates frames for each joint is depicted in fig. 2 and the DH parameters are listed in Table I. Details about DH convention and methodology can be found in [10], [13], [19].

TABLE I

DH PARAMETERS FOR OUR 5 DOF MANIPULATOR.

Joint	θ	d (cm)	a (cm)	α
1	θ_1	0	6.875	90°
2	θ_2	0	16	0°
3	$\theta_3 + 90°$	0	0	90°
4	$\theta_4 + 180°$	13.775	0	90°
5	$\theta_5 + 180°$	0	0	90°
6	0°	11.321	0	0°

Following the DH methodology with the DH parameters in Table I, it is possible to obtain the *general transformation matrix*. This matrix expresses the position and orientation of the gripper with respect to the arm's base 1. The elements of this matrix, for the five DOF arm, are presented in 2. In (2), C_5 stands for $Cos(\theta_5)$ and S_{23} for $Sin(\theta_2 + \theta_3)$.

$$T = \left[\begin{array}{ccc|c} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \tag{1}$$

The forward kinematics as we mention before calculates the position and orientation of the hand from a set of joint values. Nevertheless, it is necessary for the robot to determine the joints values of the robot to reach a desired position and orientation. There are different methods to achieve this. The method used by United4 is the *Resolve Motion Rate Control (RMRC)*. RMRC performs smooth movements of the manipulator from the current position of the hand to a desired position. This methods is for continuous paths, which means that the hand of the manipulator reaches one target and it does not have to change all its joint configuration to find a new position. Instead, RMRC tries to minimize the kinetic energy, which causes less movements of the joints configuration.

$$\begin{aligned}
n_x &= -C_5(C_1S_{23}C_1 - S_1S_4) - C_1C_{23}S_5 \\
n_y &= -C_5(S_1S_{23}C_4 + C_1S_4) - S_1C_{23}S_5 \\
n_z &= C_{23}C_4C_5 - S_{23}S_5 \\
o_x &= S_1C_4 + C_1S_{23}S_4 \\
o_y &= -C_1C_4 + S_1S_{23}S_4 \\
o_z &= -C_{23}S_4 \\
a_x &= C_1C_{23}C_5 - S_5(C_1S_{23}C_4 - S_1S_4) \\
a_y &= S_1C_{23}C_5 - S_5(S_1S_{23}C_4 + C_1S_4) \\
a_z &= S_{23}C_5 + C_{23}C_4S_5 \\
p_x &= a_1C_1 + a_2C_1C_2 + d_4C_1C_{23} + \\
&\quad d_6(C_1C_{23}C_5 - S_5(C_1S_{23}C_4 - S_1S_4)) \\
p_y &= a_1S_1 + a_2S_1C_2 + d_4S_1C_{23} + \\
&\quad d_6(S_1C_{23}C_5 - S_5(S_1S_{23}C_4 + C_1S_4)) \\
p_z &= a_2S_2 + d_4S_{23} + d_6(S_{23}C_5 + C_{23}C_4S_5)
\end{aligned} \tag{2}$$

To understand *RMRC* we first have to understand the *Jacobian control* (3). The Jacobian operator (J) relates the differential change in position of the joints (Dq) to the differential change in the hand position (D) [8].

$$D = JDq \tag{3}$$

In order to know the joints' velocities necessary to accomplish a change of position in the hand we use the inverse Jacobian. Inverting the relation of (3) as it is presented in (4) provides the basis for *RMRC*.

$$Dq = J^{+}D \tag{4}$$

Equation (4) produces a *minimal norm solution*, which is the solution that minimizes the joint values. we can also introduce a second criteria (ϕ) to be minimized subject to the primary position task by using the *global solution* (5).

$$Dq = J^{+}D + (I - J^{+}J)\phi \tag{5}$$

In both (4) and (5) J^{+} is the pseudoinverse matrix of J. The reason for use the pseudoinverse matrix is because our jacobian matrix is not square. Therefore, J^{+} is used along with a function that tries to maintain the joint values in the center, in (5) to calculate the incremental changes in the joint variables θ_i which could produce the desired incremental change in the hand's location. Details of the kinematics equations and the Jacobian for the pioneer arm can be found at [5], [6].

IV. IMITATION OF BODY MOVEMENTS

The first step in imitating a body movement is to identify the body part we want to imitate. When humans observe a body movement they do not focus their attention on every single body part. Instead, humans focus their attention on the "end-effector", discarding the position of the other body parts [11], [12]. The body schema finds the necessary body configuration for the rest of our body's parts thereby satisfying the target position for the end-effector.

If a child would like to imitate a body movement, e.g. a waving hand, the child would focus on the position of the hand, ignoring the positions of all the others parts of the body. The body schema allows the child to do this because it finds the correct configuration for all the body parts satisfying the desired position. In this way, the child is able to avoid the hassle of concentrating on every single part of the body that the child is observing.

The above example works when the demonstrator and the imitator have a common body representation. This implies that the body schema of the imitator is, by itself, capable enough to understand the demonstrator's body. Nevertheless, in a situation where the demonstrator's body differs from the imitator's body schema, there must be a way that the imitator can overcome this so called "correspondence problem" [17], [18]. For our implementation, this correspondence problem is presented when the robot, as imitator, and the human, as demonstrator, have different bodies. To work out this situation, the robot is provided with the representation of the body of the demonstrator and a way to relate this representation to its own [6].

Figure 3 presents the correspondence between the body of the demonstrator and that of the imitator. Here, a transformation is used to relate both representations. This transformation is based on the knowledge that in the set of joints of the demonstrator there are three points that represent an arm (shoulder, elbow, and wrist). The remaining two points (the head and the neck) are used just as a reference. This information about the representation of the demonstrator is extracted by means of color segmentation.

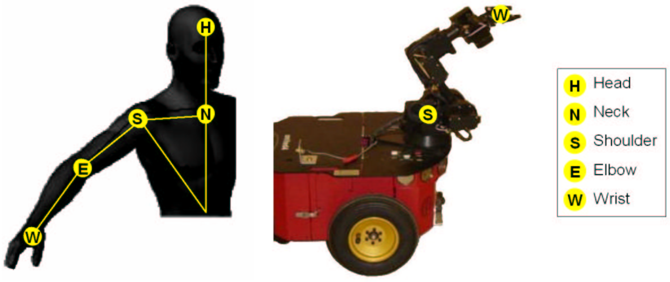


Fig. 3. The correspondence between the bodies of the demonstrator (left) and the robot (right). Two joints, the shoulder and the wrist, have correspondence in both bodies.

The reference points are used to keep a relation among the distances in the demonstrator model. The shoulder is the origin of the workspace of the robot. Thus, the shoulder of the demonstrator is used to convert the position of the remaining two points of the demonstrator's arm. The new position of the demonstrator's end-effector (wrist) is then calculated, and finally it is fitted into the actual workspace of the robot.

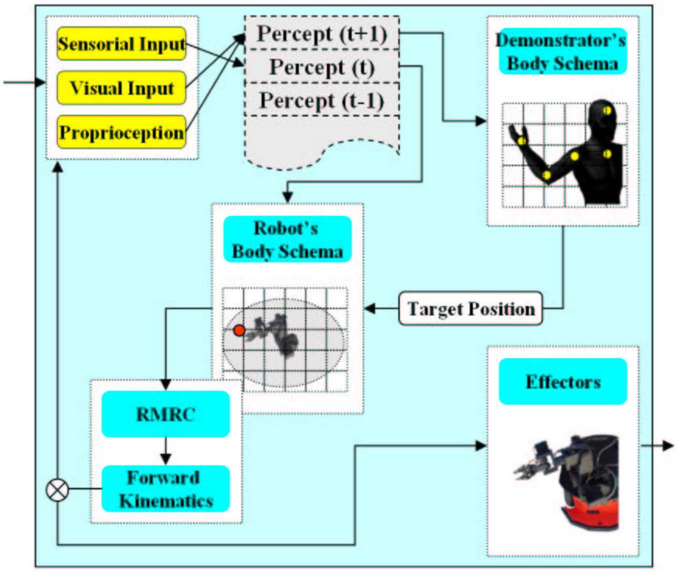


Fig. 4. The architecture used to achieve imitation of body movements. The interaction of the body schema and the body percept to achieve a new position, is depicted here.

The new position in the workspace of the robot, then, is fulfilled by its body schema. Since the robot only cares about the position of the end-effector, it uses kinematic methods to obtain the rest of the configuration [6] (Fig. 4).

The trajectories extracted here consist of a set of points of the end-effector of the demonstrator. Each point represents both the position (defined in Cartesian coordinates by x, y, and z) and the orientation (defined by the $roll, pitch$, and yaw angles).

V. IMITATION OF ACTIONS ON OBJECTS

In learning by imitation the robot should be able to identify the goals of perceived actions, instead of only identifying the physical positions. Thus, once a goal has been identified, there are different physical positions that can lead to the same goal. Hence, the essential effects of the observed action are imitated rather than just the particular physical motions. An imitated action that is based only on physical movements might fail when it is reproduced in some altered environment or when the demonstrator's body is different from the robot's body [18].

Our mechanism of imitation intends to match the perceived state of the demonstrator with an action, which once executed would produce a similar state to the one perceived of the demonstrator. This mechanism of imitation is able to identify the goals from the observed actions, which would allow the adapting of actions to different conditions of the environment.

The environment-robot relation is represented by abstract states in the body percept. These state variables record the condition of the environment at a given instant, much like a snapshot.

The body percept, as has been mentioned, is the robot's perceptual inputs at any given instant (t). The robot's percept sequence can be thought of as a history of what the robot has perceived during its lifespan [22].

The condition of the environment can be modified by the robot's actions. In general, the robot's choice of action at any given instant depends on the entire percept sequence observed to date. However, to analyze all the body percepts in the sequence makes the selection of an action a tough job. To present a better approach to this problem, the actions can be selected based on the current percept state and the goal state that the robot has to achieve. Thus, the representation of an action has the following characteristics:

- *Preconditions,* which are state values that must be met before the execution of the action. These state values are contained in the current robot's body percept (t).
- *Postconditions,* which are state values obtained after the execution of the action. These states comprise the next robot's body percept ($t+1$). The action's postconditions are interpreted as the embedded goals of the action [16].

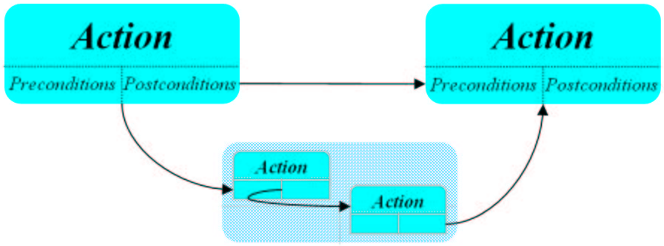


Fig. 5. Action representation. An action has preconditions that must be met before the action can be executed. The postconditions are the goal achieved after the action is performed. Complex action are represented as net of actions.

The robot's body schema has been equipped with a set of *primitive* actions, which are the basic actions that the robot can perform. The robot is able to build complex actions by using these primitive actions. The representation of a complex action is a net of actions connected by preconditions and postconditions (fig. 5). This net corresponds to a plan to achieve a particular task. The actions in the net could be either primitive actions or complex actions. This set of primitive actions is essentially outlined by the *robot-environment states* that the robot is able to recognize.

The *robot-environment states'* values of the body percept are calculated in some cases by using the current reading from the sensorial, visual, and proprioception data. For example, the value for *Gripper State* is obtained directly from the sensory input, checking if the gripper is either closed or open. Nevertheless, in some cases we not only use the current sensorial readings at time t, but also those of previous states of the percept sequence $t-1, t-2, \cdots, 0$ as well. For example, in the case of the value of *Approaching,* the robot uses the previous states to check if the end-effector was far from an object, and if it is getting closer to that object.

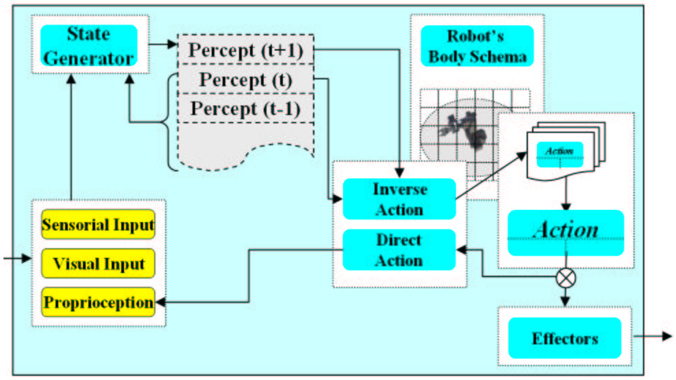


Fig. 6. The interaction of the body percept and the body schema, when the robot system is learning. the output from an action can be inhibited to the effectors, which will produce a mental rehearsal of the action.

The body schema not only contains information about the physical parts of the body, but it also keeps the knowledge of which actions can be performed. This knowledge about feasible actions is supposed to be used to recognize those actions when they are executed. Therefore, we can distinguish two main functions of the body schema regarding actions:

- *Direct action,* which is when the robot has an action to perform and the preconditions, in the current body percept(t), are met. Then the action is taken and the goal of the action is achieved.
- *Inverse action,* this situation arises when the robot knows the goal that it has to achieve, which is contained in the body percept($t+1$). Besides, the robot knows its current body percept(t), which is a pool of possible preconditions. Thus, the robot can look an action up in its repertoire. That action would need to satisfy the goal and its preconditions must be met.

These two functions of the body schema are important to achieve imitation. The inverse action is used to identify the action performed by the demonstrator, while the direct action predicts the next body percept. Here, the imitator can either perform the action and send its signals to the effectors, or it can inhibit the physical motion thereby producing a mental simulation of the action.

The relation between the body schema and the body percept changes depending on whether the robot is learning or performing an action. When the robot is learning, the body percept contains the effects of the demonstrator's actions upon the environment. This is because the system is simulating the states of the demonstrator in order to identify the actions. When a new action is performed a new body percept($t+1$) is created. This would act as the goal that the robot would need to reach from its current body percept(t). The inverse action function of the body schema, is then able to select an action that covers the criteria. In addition, the direct action function can predict the states generated after the execution of the action, which complement the states in the body percept(t+1). This learning process is depicted in fig. 6.

When the robot is executing an action, the body percept(t) includes all the states of the robot and the state of the relation of environment-robot. The action that will be executed is then given to body schema, or more specifically to the direct action function. Here, it is first checked that the preconditions of the action are satisfied by the states in the current body percept(t). The action will not be executed if the preconditions are not met. Once the precondition are met, the action is decomposed into the sub-actions that are part of the net of actions. A sub-action is taken when its preconditions are satisfied. The execution of a primitive action requires looking for the action into the library. On the other hand, to execute a complex action *the direct action function* has to make a recursive call for each single action that compounds its net, until it finds the primitive actions. *The direct action function* also monitors that the effects of the executed action are obtained, by checking them in the body percept($t+1$).

VI. EXPERIMENTAL RESULTS

To investigate the abilities of the approach presented, we described our experience with experiments of imitation of body movements as well as imitation of actions on objects. In our set-up we used the robot United4, as the imitator, which faced a human demonstrator. The robot observed the movements performed by the demonstrator and tried to imitate them. The experiments were conducted in two phases for all the cases:

- *Learning phase,* in which the robot was observing the demonstrator's actions, while identifying the actions and recording them to be executed later.
- *Execution phase,* here the robot was set in an environment, which could be the same to that it observed, or similar, and it must perform the actions learnt from the previous phase.

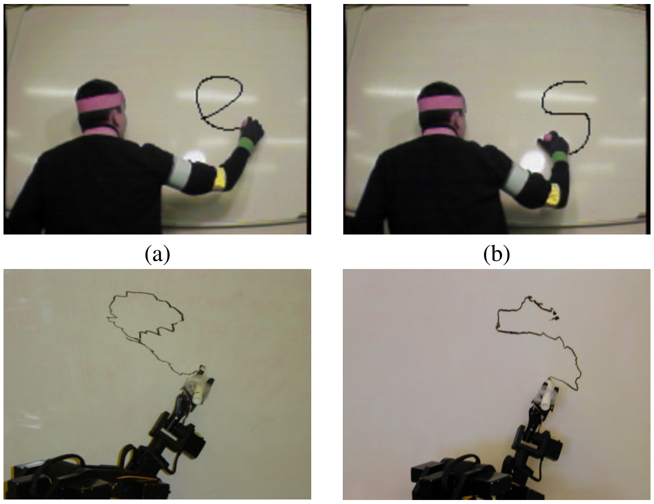
The experiments have been conducted in our Brooker laboratory. The relevant objects in the environment were marked with different colors, in order to take into consideration only significant information. The joints of the demonstrator are marked in different colors to simplify the feature extraction. The less cluttered background permits the robot to focus only on the relevant features.

The path was extracted and adjusted in order to be performed by the robot since the size and shape of the workspace for the model and the robot were not the same.

We could observe that the robot presented *the mirror effect*. This effect is when the demonstrator is located in front of the robot and moves its right arm, then the imitator would move the arm on the left side, acting as a mirror.

The experiments on imitation of body movements involved observing the movements of the demonstrator's hand and then the execution of those movements by the robot. The movements used in the experiments generated different letters, e.g. e,s.

The robot observed the demonstrator performing the handwriting whereas, by means of the colored markers that the demonstrator wears, the body representation of the demonstrator was extracted. This representation was related with the robot's representation by the body schema. Therefore, the robot could understand the new position of the demonstrator's end-effector within its workspace. The configuration needed to reach this desired position was eventually calculated by means of the kinematics methods. Finally, the path described by the end-effector was recorded and was ready to be executed.


(a) (b)

(c) (d)

Fig. 7. Learning phase, in (a) and (b) the demonstrator is writing the letters "e" and "s". Execution phase, in (c) and (d) the robot is writing those letters.

Figure 7 presents the letters "e" and "s." The learning phase is presented in (a) and (b), where the demonstrator has written these letters. When the demonstrator was describing the path of these letters, the robot was observing and relating those movements to its own. In the execution phase, (c) and (d), the robot is performing the paths described by the letters. The path written by the robot is shaky and rough, not smooth as the one described by the demonstrator. This is because, the color information used to represents the demonstrator is not stable, it is "noisy" and this causes the learnt path to be spiky. This situation can be appreciated with more detail in fig. 8

and fig. 9, which show the learnt path in a dotted line and the robot path in a solid line.

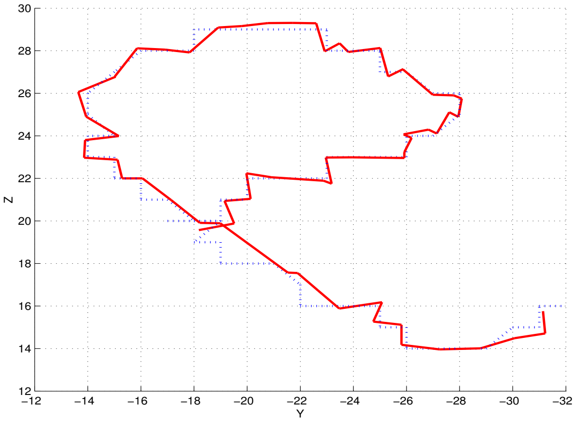


Fig. 8. Letter "e." The Performance of the robot in the solid line (from fig. 7.c), and the dotted line is the path that the robot generated by observing the demonstrator performance(from fig. 7.a).

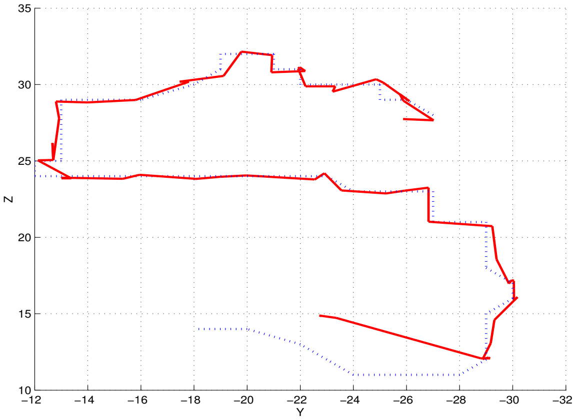


Fig. 9. Letter "s." The Performance of the robot in the solid line (from fig. 7.d), and the dotted line is the path that the robot generated by observing the demonstrator performance(from fig. 7.b).

Regarding the experiments of imitation of action on objects, the robot was observing the demonstrator open a small fridge. Here, the robot was collecting not only data of the demonstrator but also information about the *relevant objects* in the environment.

For these experiments the robot was endowed with a set of primitive actions. This set of primitive actions is mainly defined by the environmental states that the robot is able to recognize. The body percept is structured by both the position of the demonstrator's end-effector and the states that represent the relation environment-robot. The state generator contains rules defining the behaviour of the relation robot-objects in the environment. For example, for the action *Carrying* an object the object must be in the gripper, and moving at the constant motion with the gripper.

In figure 10, the demonstrator shows the actions in (a), (c), and (e). The robot is performing a those actions in (b), (d), and (f). The description of the actions performed by the robot and theirs associated preconditions and postconditions appear in the table II. First, it looks for the fridge's handle, once this has been found (*Search*), the robot approaches to it (*Approach*). When the robot is close enough to reach the object with the arm it stops, this behaviour has been programmed in this way, since the robot is unable to estimate the distance from the camera image. The object is then centered in the image, so the arm can stretch (*Reach*) and grab it (*Grab*).

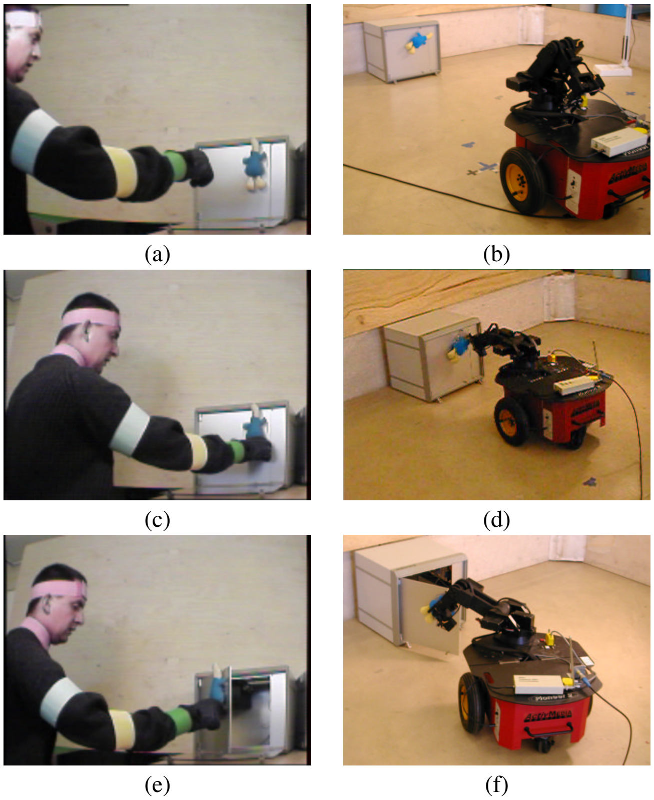

(a)
(b)
(c)
(d)
(e)
(f)

Fig. 10. Learning phase, (a) the demonstrator is approaching to the fridge, (c) the demonstrator is grabbing the handle of the fridge, and (e) opening the fridge's door. Execution phase, (b) the robot is looking for the fridge handle, in (d) the robot has approached to the object and grabs it, and (f) robot moving the fridge handle therefore, opening the door.

In all the previous actions there is only one parameter the object involved, the fridge's handle. However, for the last action, *Carry*, we required two parameters: the object and the path to be follow by the arm. Thus, the arm is moving describing the path shown by the demonstrator as it is carrying the object, or to be most specific, pulling the object in this case.

VII. CONCLUSIONS AND FUTURE WORK

Roboticists have begun to focus their attention on imitation. Since the capability to obtain new abilities by observation represents many important advantages, imitation intends to fill the gap to build *social robots*. Imitation also seems to be a tool to acquire new behaviors and to accommodate these within new contexts. Imitation then would just be seen as a tool that robots use to acquire new knowledge, which could be applied to a variety of problems and not only as a mechanism to solve a specific one.

TABLE II

STATE VALUES FOR THE ACTIONS USED IN THE OPENING FRIDGE TASK.

	Search(Obj)		Approach(Obj)		Reach(Obj)		Grab(Obj)		Carry(Obj,Path)	
	Precond	Postcond	Precond	Postcond	Precond	Postcond	Precond	Postcond	Precond	Postcond
Object	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ObjMoving	-	-	-	-	No	No	No	No	-	No
Grip-Obj	-	-	Far	Close	Close	Touch	Touch	Touch	Touch	Touch
ArmMoving	-	-	-	-	-	No	No	No	-	No
GripState	-	-	-	-	-	Open	Open	Close	Close	Close

Learning by imitation presents considerable advantages in contrast with traditional learning approaches. Imitation might equip robots with the abilities to be efficient in applications requiring human interaction. In addition, the robots would eventually present a better interaction and be ready to help humans in personal tasks.

We describe our approach based on *the body schema* (which is the body representation and contains the physical limitation as well as the feasible action that the body can perform) and *the body percept* (which is the position of the body parts at a given instant, in addition it keeps the relation of the body with the environment). These two key-parts play a crucial role to achieve imitation. We used an approach of four developmental stages of imitation in humans, to prove the key-role of these two components. The scope of this paper describes our progress on the following three stages:

- *Body babbling.*
- *Imitation of body movements.*
- *Imitation of actions on objects.*

For body babbling we argue that a control method is a good way to endow the robot with a model to describe its body configuration (body schema). In this way we avoid a random trial-and-error learning process, as that presented in infants. In the second stage, imitation of body movements, we use the idea of focusing on the end-effector as humans do and obtaining the rest of the configuration from the body schema. Thus, the robot's body could satisfy the target position for its end-effector. The last part of our work, imitation of actions on objects, involves the identification of an action by using the body schema and using the body percept as the target goal.

We have also described our experiments with a robot as the imitator, imitating the movements of a human demonstrator. Our experiments show the feasibility of the proposed approach at this first stage of imitation of actions on objects. Our future work comprises further experiments at the stage of imitation of action on objects, increasing the complexity of the tasks of the robot, as well as increasing the level of human-robot interaction.

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