Robust Semantic Representations for Inferring Human Co-manipulation Activities even with Different Demonstration Styles

Karinne Ramirez-Amaro, Emmanuel Dean-Leon, and Gordon Cheng

Abstract—In this work we present a novel method that generates compact semantic models for inferring human coordinated activities, including tasks that require the understanding of dual arms sequencing. These models are robust and invariant to observation from different executions styles of the same activity. Additionally, the obtained semantic representations are able to re-use the acquired knowledge to infer different types of activities. Furthermore, our method is capable to infer dual-arm co-manipulation activities and it considers the correct synchronization between the inferred activities to achieve the desired common goal. We propose a system that, rather than focusing on the different execution styles, extracts the meaning of the observed task by means of semantic representations. The proposed method is a hierarchical approach that first extracts the relevant information from the observations. Then, it infers the observed human activities based on the obtained semantic representations. After that, these inferred activities can be used to trigger motion primitives in a robot to execute the demonstrated task. In order to validate the portability of our system, we have evaluated our semantic-based method on two different humanoid platforms, the iCub robot and REEM-C robot. Demonstrating that our system is capable to correctly segment and infer on-line the observed activities with an average accuracy of 84.8%.

I. INTRODUCTION

Enabling robots to learn new tasks typically requires that humans demonstrate the desire task several times [1]. This implies that the acquired models will greatly capture the execution style of the person demonstrating the desired activity. This however, could lead to a major problem for the generalization of the acquired model, since it will be almost impossible to teach robots all possible variations of one specific activity. Then, the ideal case is to enable robots with reasoning mechanisms to allow them to learn new activities by generating a model that interprets the demonstrated activities in a general manner, thus allowing the inclusion of different variations of the same activity.

Even when it is possible to observe stereotypical and predefined motion patterns from repetitive human movements [2], the execution of an activity or a similar activity can be performed in many different forms depending on the person, the place or the environment constraints. In other words, everybody has its own style to perform a desired activity. For example, Fig. 1 shows at least three different real-life demonstrations of the activity cutting the bread performed by random people. We can observe that the first participant is using a common style of holding the bread with his left hand and execute the cutting activity with his right hand, Fig. 1.b.1. In a different form, the participant in the middle chooses to roll the bread with his left hand while cutting the bread with his right hand, Fig. 1.b.2. Finally, the third participant, which is left-handed, holds the bread with his right hand and cuts the bread with his left hand, Fig. 1.b.3. This indicates that we need to design a system that should handle all these different execution styles.

In our previous work [3], we presented a system which allows our iCub humanoid robot to extract the meaning of human activities using our proposed hierarchical approach to obtain semantic models. Later, we extended our system by including the activity recognition of both hands at the same time as presented in [4]. Even when our system is able to recognize activities of both hands, it was limited to only execute the activities of a single hand. Then, this paper enhances our current system in the following forms: a) we add robustness to variations on the demonstration styles for different activities; b) then, we include a method to tackle the problem of co-manipulation activities; c) finally, we improve the portability of our system and we tested it in two different humanoid platforms.

This paper is organized as follows, Section II presents the related work. Then, Section III describes the main modules of the presented system. Afterward, Section IV explains the steps to extract the low-level features. Then, Section V presents the semantic representations method. Section VI introduces the transference of the semantic models to
humanoid robots. Finally, section VII briefly expresses the obtained results followed by the conclusions.

II. RELATED WORK

Learning and understanding human activities can greatly improve the transference and generalization of the acquired knowledge among different robotic platforms. These robotic platforms have different embodiments and different cognitive capabilities [5], therefore the transference of trained models from one platform to another is not straightforward and typically the obtained models work fine only for the tested platforms [6]. However, if instead of learning how the motions are executed, we learn the meaning of such movements, then we can transfer these learned models to different situations and among different robotic platforms as proposed in this work.

Segmenting and recognizing human activities from demonstrations have been (partially) achieved using human poses mainly observed from external videos, e.g. using Conditional Random Fields (CRF) [7], Dynamic Time Warping [8], or by encoding the observed trajectories using Hidden Markov Models (HMMs) mimesis model [9]. However, the above techniques realize on the generation of trajectories which depend on the location of objects and human postures, this means that if a different environment is being analyzed or its executed by a different demonstrator, then the trajectories are altered completely, thus, new models have to be acquired for the classification, this implies that the proposed techniques need considerable time to finally learn a specific task [1]. Additionally, such techniques require a sophisticated visual-processing method to extract the human poses [10].

Recent studies focus on determining the levels of abstraction to extract meaningful information from the produced task to obtain what and why certain task was recognized. Hierarchical approaches are capable to recognize high-level activities with more complex temporal structures [11]. Such approaches are suitable for a semantic-level analysis between humans and/or objects which can be modeled using object Affordances to anticipate/predict future activities [12], or using Graphical Models to learn functional object-categories [13], or Decision Trees to capture the relationships between motions and object properties [3]. For example, [14] suggests to use a library of OACs (Object-Action Complexes) to segment and recognize an action using the preconditions and effects of each sub-action which will enable a robot to reproduce the demonstrated activity. However, this system requires a robust perception system to correctly identify the object attributes which are obtained off-line. Based on the OACs principle, Yang et. al. [15] introduced a system that can understand actions based on their consequences, e.g. split or merge. Nevertheless, this technique greatly needs a robust active tracking and segmentation method to detect changes of the manipulated object, its appearance and its topological structure, i.e. the consequences of the action. Then, based on the affordance principle, Aksoy et. al. [16] presented the called Semantic Event Chain (SEC), which determines the interactions between the hand and the objects, expressed in a rule-character form, which also depends on a precise vision system.

III. SYSTEM MODULES DESCRIPTION

Most of the recognition systems are designed to fit perfectly the studied task, however most of these systems can not easily scale toward new tasks or to allow different input sources [6]. This section presents the overall design and main components of our proposed framework. The main advantage of our system is its levels of abstraction that enhance its scalability and adaptability to new situations. For instance, our perception module permits the use of different input sources, such as: single videos [3], multiple videos [17] and virtual environments [18] which can bootstrap the learning process.

Our framework contains four main modules (see Fig. 2): 1) Perceive the relevant aspects of the demonstrations; 2) Generate or re-use semantic rules; 3) Infer the goal of the demonstrator; and finally, 4) Execute the inferred behavior by a robot.

The Perception Module, enables robots to perceive different types of input information from different sources. This module extracts features obtained from the environment (input source), analyzes the features and generates meaningful information. Three primitive motions are segmented from the input data, i.e. move, not move and tool use. In addition, the information from the environment is also extracted, for example the objects in the scene and their properties, in our case we considered the following two properties: ObjectActedOn and ObjectInHand.

The Semantic Module represents the core of our system. It interprets the data obtained from the Perception module and processes that information to automatically infer and understand the observed human behaviors. It is responsible for identifying and extracting the meaning of human motions by generating semantic rules.

The Inference module includes knowledge-base to enhance the inference capability of our system. This is an important feature, in case of failure, the system uses its knowledge base to obtain an alternative and equivalent state of the system which contains instances of the desired class. With the knowledge-base we do not need to recompute the semantic rules every time we face a new situation.
The Robot Primitives module uses the inferred activity and enables an artificial system, i.e. allows a robot to reproduce the inferred action in order to achieve a similar goal as the one observed. This implies that given an activity, the robot needs to execute a skill plan and command the primitives from a library to generate a similar result.

Our system is based on a hierarchical approach, where different levels of abstraction are defined. This abstraction of the observation captures the essence of the activity, which means that our system is able to indicate which aspect of the demonstrator’s activity should be executed in order to accomplish the inferred activity.

A. Levels of abstraction

Studies from the Psychology and Cognitive communities suggest that goal-directed activities exhibit recurrent intercorrelated patterns of activities [19]. Inspired by the above findings we propose our two levels of abstractions:

- The first one gathers (conceive) low-level features information from the environment, i.e. atomic hand motions such as: move, not move and tool use, as well as basic object properties, e.g. ObjectActedOn and ObjectInHand, see Section IV;
- Whereas, the second part handles the difficult problem of interpreting the perceived information into meaningful classes using our proposed reasoning engine, i.e. the high-level human activities, such as: reach, take, cut, etc. (see Section V).

IV. Extracting low-level features from observations

In our previous work [3], we proposed to extract the following low-level features from observations, i.e three primitive human motions are segmented into one of the following categories:

- move: The hand is moving, i.e. $\dot{x} > \varepsilon$
- not move: The hand stops its motion, i.e. $\dot{x} \rightarrow 0$
- tool use: Complex motion, the hand is moving and it is acted on a second object, i.e. $o_h(t) = knife$ and $o_o(t) = bread$.

where $\dot{x}$ is the hand velocity. Notice, that those kind of abstract motions can be recognized in different scenarios, however these segmented motions cannot define an activity by themselves. Therefore, we need to add the object information, i.e. the motions together with the object properties have more meaning than as separate entities. The object properties that we define in this work are:

- ObjectActedOn ($o_o$): The object is acted on an object, i.e. $d(x_h, x_o) = \sqrt{\sum_{i=1}^{n}(x_{i,h} - x_{i,o})^2} \rightarrow 0$
- ObjectInHand ($o_h$): The object is in the hand, i.e. $o_h$ is currently manipulated, i.e. $d(x_h, x_o) = 0$.

where $d(\cdot, \cdot)$ is the distance between the hand position ($x_h$) and the position of the detected object ($x_o$). The output of this module determines the current state of the system ($s$), which is defined as the triplet $s = \{m, o_o, o_h\}$. The definition and some examples of the motions and object properties are further explained in [4].

Since we expect noise on the perception of these low-level features, we implemented a 2nd. order low-pass filter to smooth the obtained velocities. We choose the digital Butterworth filter with normalized cutoff frequency.

V. Inferring high-level human activities

This module receives as input the state of the system ($s$), composed by the hand motion segmentation ($m$) and the object properties ($o_o$ or $o_h$). Each of these perceived states populates the training sample ($S$), to infer the desired target function ($c$), which represents the high-level activities.

In this work, the semantics of human behavior refers to find meaningful relationships between human motions and object properties in order to understand the activity performed by the human. In order to achieve that, we use the C4.5 algorithm [20] to compute a decision tree ($T$), which learns the target function $c$ by selecting the most useful attribute ($A$) that classifies as many training samples ($S$) as possible by using the information gain measure:

$$ Gain(S, A) = \text{Entropy}(S) - \sum_{v \in \text{Values}(A)} \frac{|S_v|}{S} \text{Entropy}(S_v) $$

where Values($A$) is the set of all possible values of the attribute $A$, and $S_v = s \in S | A(s) = v$ as a collection of samples for $S$.

Our proposed method consists of two steps to recognize human activities. The first one will extract the semantics of human basic activities, this means that target concept value is of the form:

$$ Class c : \text{ActivityRecognition} : S \rightarrow \{\text{Reach, Take, Release, PutSomethingSomewhere, Idle, GranularActivity}\} $$

where GranularActivity represents the set of activities that depend on the context. Therefore, to identify such kind of activities a second step is needed [4]. This step uses eq.(1) and the new target concept value:

$$ Class c : \text{ActivityRecognition} : S \rightarrow \{\text{Cut, Spread, Sprinkle, Unwrapping, Dispose}\} $$

A. Inferring parallel activities at the same time

One of the major advantages of extracting semantic representations is its generalization capability. Even when the obtained tree ($T$) is trained to recognize the activities of a specific hand, it should be robust enough to also recognize similar activities performed by the other hand. This generalization capability is tested and exploited in our semantic-based framework, since the obtained Tree $T$ (see Fig. 4) is robust when recognizing similar activities performed by both hands at the same time, without further changes in the algorithm.

B. Co-manipulation activities

One of the features of observing people from videos is to capture the natural way that people executes everyday activities in realistic environments, as the ones used in this work. However, the correct recognition of parallel activities sometimes is not enough, especially when dealing with collaborative activities, e.g. co-manipulation where two
hands work together to achieve a common goal. In this case, the correct activity recognition and their correct order of execution (synchronization) are both highly important to achieve the desired task.

For instance, in the case of cutting the bread task (see Fig. 1), it is important that the system first detects that the left hand moves the bread to the desired position before cutting the bread with the right hand. In order to cope with the co-manipulation problem, we proposed to build on demand a dependency table that will store the sequence where the observed activity is inferred as well as the hand executing such activity, as shown in Fig. 3.

From the obtained dependency table depicted in Fig. 3, our system is able to automatically generate execution sequences for the collaborative task from observations. For example that activity \( A_1 \) has to be executed by both hands at the same time. Then, activity \( A_2 \) of the right hand has to be executed before the activity \( A_3 \) of the left hand, in other words, the activity \( A_2 \) of the left hand, should not be triggered before \( A_2 \) of the right hand has finished. The system can identify when an activity has finished using the Robot primitive module of each hand. This module triggers different event flags for each activity: a) initialized, b) running or c) finished.

This analysis is very important since the activity recognition of each hand is made in parallel in our system and no information regarding the execution steps is known a priori. Additionally, when transferring our semantic-based system into robots, the correct execution sequence has to be considered to successfully achieve the desired collaborative task. This means that without the proposed dependency table, the correct execution sequence can not be guaranteed, thus leading to problems such as executing the cutting activity on the table instead of on the bread.

VI. TRANSFERRING THE MODELS INTO HUMANOID ROBOTS

As a final step, we validate our framework on two humanoid robots\(^1\), the iCub humanoid robot which has 53 degrees of freedom [21], and REEM-C a full-size biped humanoid robot\(^2\). To control the iCub robot, our system has been implemented in YARP as explained in our previous work [4]. However, for controlling the REEM-C robot we needed to transfer our modules into ROS. Then, to enable the recognition of both hands at the same time, we exploit the advantages provided by ROS using the name space property for launching the same process multiple times in parallel.

It is important to highlight that the robotic system retrieves on-line the pose of the perceived hand and object(s) in the scene from the perception module, which triggers the activity recognition module, this means that the used videos have not been labeled in any way and the recognition is performed in real-time. This module sends the inferred activity to the Robot Primitive module to execute the proper primitive on the robot. For the REEM-C robot we have implemented the different skills for both arms in joint space. The Perception module obtains the 6D pose of the objects in the Cartesian space, and the desired joint position is computed using the Moveit!\(^3\) package in ROS. This desired position is the reference for the local joint position controller. For the grabs primitive, a predefined grasp pose has been implemented, however more sophisticated controllers can be used such as the one proposed in [22].

VII. RESULTS

For the obtained results, we use two data sets: pancake and sandwich making, which are publicly available\(^4\). The first one contains recordings of one human making a pancake several times. The second data set contains a more complex activity, which is making a sandwich performed by eight random subjects under two time conditions, i.e. normal and fast. This section presents the achieved results in two parts. First, we present the semantic representations obtained using our proposed method. Then, we present some results from the on-line implementation on the iCub and the REEM-C humanoid.

A. Results of human activities recognition

As mentioned in Section V, our proposed method consists of two steps to recognize human activities. For the first step, we use the information of the ground-truth\(^5\) data of the first subject for the scenario of making a sandwich. We split the data as follows: the first 60% of the trails is used for training and the rest 40% for testing. Then, we obtained the tree \( T_{\text{sandwich}} \) shown in the top part of Fig. 4 (magenta box) which infers the basic human activities defined in eq. (2).

Afterward, we apply the second step of our algorithm to further classify the GranularActivities, defined in eq. (3) and the extension of our tree is obtained as shown in the bottom part of the tree (\( T \)) depicted in Fig. 4.

We tested the accuracy of the obtained tree \( T_{\text{sandwich}} \) using the remaining 40% of the sandwich data set to validate

\(^1\)Another advantage of our proposed framework is its multi-robotic platform modality, in this case YARP (http://wiki.icub.org/yarp/) and ROS (http://wiki.ros.org/)
\(^2\)http://pal-robotics.com/en/products/reem-c/
\(^3\)http://moveit.ros.org
\(^4\)http://web.ics.ei.tum.de/ karinne/Dataset/dataset.html
\(^5\)The ground-truth was manually labeled by a person considered as an expert since this person received a training session.
the robustness of the obtained rules. Then, given the input attributes \( n_{sandwich, test} = \{ \text{Move, Something, None} \} \) we determine \( c(n_{sandwich, test}) \). Afterward, the state-value pairs from the test data set \( n_{sandwich, test} \) are of the form \( \langle n_{sandwich, test}(t), \pi \rangle \), where \( t \) represents the time (frames). After that, the target value is determined for each state of the system \( c(n_{sandwich, test}(t)) \). Finally, the obtained results show that \( c(n_{sandwich, test}(t)) \) was correctly classified 92.57\% of the instances using as input information manually labeled data, i.e., during the off-line recognition.

### B. Robot execution results

The next important step is to extend our system from off-line to on-line recognition using the Color-Based technique as presented in [4]. This implies that we use as input the data obtained from the automatic segmentation of human motions and object properties from the perception module in order to test the on-line recognition using the obtained tree \( T_{sandwich} \). Compared with our previous work, we have improved the performance of our algorithm and the obtained results are presented in Table I.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Accuracy of recognition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut the bread (Common style-S01)</td>
<td>90.64</td>
</tr>
<tr>
<td>Cut the bread (rolling the bread-S04)</td>
<td>94.32</td>
</tr>
<tr>
<td>Cut the bread (left-hand style-S06)</td>
<td>74.41</td>
</tr>
<tr>
<td>Pour the pancake</td>
<td>84.42</td>
</tr>
<tr>
<td>Flip the pancake</td>
<td>79.18</td>
</tr>
</tbody>
</table>

First, we implemented our system in the iCub robot. In this case, we tested the data set of pancake making only for the right hand, where the activity pouring has not been included in the semantic model. However, from Fig. 4 it is possible to observe that the obtained taxonomy is preserved among the granular activities. This means that our system is able to learn new rules on demand using active learning methods. Thus, when the iCub recognizes that it does not know the new demonstrated activity, the system requires that the user provides a label for the new activity, in this case the label pour. Therefore, a new branch on the tree \( T_{sandwich} \) is included to recognize this new activity in the future. Even when the system recognizes a new activity, this does not affect the inference accuracy, which in this case the average accuracy for both hands is 84.42\%. A similar procedure is followed for the activity flip with an average recognition accuracy of 79.18\%.

Another improvement of our system is its portability into different robotic platforms, taking into account a more complex scenario which includes parallel activities in collaboration. In this new scenario, the REEM-C robot must perform sequential activities with both hands. In this case, we are re-using the same semantic tree \( T_{sandwich} \) to identify activities either for the right or the left hand, without affecting the recognition performance. Furthermore, the robot infers that the activity reaching is detected for both hands, therefore the robot executes both activities at the same time.

In addition, the system has been tested in a more complex case, depicted in Fig. 5. Here, the demonstrator performs the cutting activity in an odd-fashion, where she rolls the bread during the execution. Even with this odd-variation on the observation, our system is able to correctly infer the cut activity. Thus, demonstrating the robustness of our obtained semantic representations to the variations on the demonstrations of the same activity. Additionally, we observe that the left hand is executing the correctly recognized activity of taking the bread, preserving the correct sequence for the collaborative actions.

Notably, for these demonstrations of the same activity, we test the robustness of the obtained models, this means that no further training was performed to include the variance presented in these new observations. The average accuracy for the on-line segmentation and recognition of the overall activities for the scenarios shown in Table I is 84.8\% for both hands. In our previous work [23], we concluded that the correct segmentation and recognition of human activities is not unique and greatly depends on the person interpreting the motions, especially when both hands are involved. The following link presents a video with more details about all these experimental results: http://web.ics.ei.tum.de/~karinne/Videos/RamirezDChumanoids15.avi

### VIII. Conclusions

One major problem of interpreting human everyday activities from observations is the fact that they greatly depend on the execution style of the person demonstrating the activities, leading to variations in the demonstrations. Although, each person has his/her own way of executing the same task, we (humans) have the capability to interpret all these different variations, since we abstract the meaning of the observations. Therefore, in this work we presented a framework that can deal with such problems in a robust manner with an on-line accuracy of recognition around 84.8\%. Furthermore, our system can handle parallel activities in both cases: a) independent activities and b) in the more complex situation where the activities are sequential and collaborative, e.g. co-manipulation.

Our proposed method is able to automatically segment and recognize dual-arm human activities from observations using
semantic reasoning tools. Our presented system is flexible and adaptable to different variations of the demonstrated activities, as well as to new situations due to the re-usability of the learned rules, which allows the integration of new behaviors. Furthermore, our presented multilevel framework is applicable across different humanoid robots.

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