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# SAMI: Interactive, Multi-Sense Robot Architecture

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***Abstract*—The design and development of robotic agents to be deployed in the real world for human-robot interaction (HRI) purpose require adequate robot architecture. In this paper, we present a new, middle-out robot architecture which extends the reactive paradigm by adding an interactive layer, leading to the *Sense-Act-Modulated-by-Interactions (SAMI)* architecture. This proposed SAMI robot architecture has been embodied by a mobile, multi-modal, SAMI-based robot and successfully validated by carrying out tests of the SAMI embodiment in real-world, unstructured environment.**

***Index Terms*—Intelligent Robotics, Cognitive Robot Architecture, Robot Perception, Machine Vision, Cybernetics, Software-Hardware Design, Human-Robot Interaction, Human-Machine Cooperation and Systems, Companion Robots.**

## I. INTRODUCTION

With the growth of robotic applications and robot services in our daily life, the development of appropriate architectural models [1], [2] for these robotic agents is necessary [3], [4]. Thence, different approaches to design robots and their architectures have been proposed over time [5].

The first robots [6] adopted the *deliberative* paradigm as illustrated in Fig. 1(b), which consists of the sequence of the sense-plan-act functions. Hence, the robot firstly senses the world; the sensing data being used to build a global world model under the closed-world assumption. Then, the robot plans the corresponding action by means of an automated planner such as STRIPS [7], based on the sensed data and/or the world models. Next, the robot acts accordingly, e.g. by executing the planned task. This top-down approach leads to hierarchical architectures which usually suffer from slowness, since the robot needs to plan at a high level and then act, before sensing at low level again.

To overcome this drawback, the *reactive* paradigm displayed in Fig. 1(a) has been proposed. It directly connects robot's sense and act functions, without the need to model the world since 'the world is its own best model' [8]. This paradigm has generated the behaviour-based robots which are characterized by a decomposition of robot behaviours in independent and concurrent behaviours, each modeled e.g. by a finite-state machine augmented by a clock and performing a specific, limited task. This bottom-up approach is the basis of subsumption architectures [8] and is effective, since the input to each act is the output of a sensor. However, this approach is task oriented, and predicting its global behaviour is uneasy.

The *hybrid* paradigm [9], as shown in Fig. 1(c), is mostly used nowadays. It allows robots to decompose a task into sub-tasks or mission planning and to deliberately plan what are the suitable behaviours to accomplish each sub-task; the behaviours being executed as per reactive paradigm coupling the sense-act functions. Therefore, this approach combines both deliberative and reactive paradigms in a heterogeneous architecture such as the three-layer architecture [10], where the deliberative layer provides high-level reasoning using automated planning, while the reactive layer ensures the low-level control of the robot, and the executive layer or sequencing layer glues one layer to the other one, keeping track of the robot's history.

On the other hand, in today's robotic applications such as companion robots, human-robot interaction (HRI) is crucial. HRI could be characterized by five factors identified by [11], such as (i) the level of autonomy [12], (ii) the nature of the exchanged information [13], (iii) the structure of the team [14], (iv) the adaptation, learning, and training of the person and the robot [15], and (v) the shape of the task [16].

Existing robot architectures involving HRI have been built on different paradigms, i.e. the deliberative [17], the reactive [18], or the hybrid one [19], [20], [21], [22]. The resulting robots present limited HRI limited, e.g. focused mainly on collision avoidance [17], restricted to keyboard-based communication [17], delayed due to robot's idling state waiting for human [18], or based on only a single sensor [20]. Besides, interactive architectures such as B3IA (Behaviour-Based Behaviour Intervention Architecture) [19], ACT-R (Adaptive Character of Thought-Rational) [21] and its embodiment ACT-R/E (Adaptive Character of Thought-Rational/Embodied) [22] rely heavily on prior knowledge and world models.

Hence, in this paper, we present a new robot architecture (Fig. 2) which is interactive as well as computationally efficient and which relies on the Sense-Act functions Modulated by the potential Interactions (SAMI), fully addressing the (i)-(v) HRI features.

Indeed, the SAMI architecture allows the sense function to get multi-modal inputs unlike [20]. Moreover, the SAMI architecture does not involve any user's models because we consider 'the user knows him/herself better than anyone else'. This latter assumption speeds up both the act/interact processes and also allows the robot to swiftly adapt to any team of any size and type of teammates.

It is worth noting a SAMI-based robot could be autonomous or semi-autonomous depending of the level of HRI as per machine intelligence model [12].

The contributions of this paper are twofold. On one hand, we introduce the interactive robot architecture consisting in robot's *Sensing-Acting-Modulated-by-Interacting (SAMI)* functions. On the other hand, we present the embodiment of the SAMI architecture into the SAMI-based robot pet

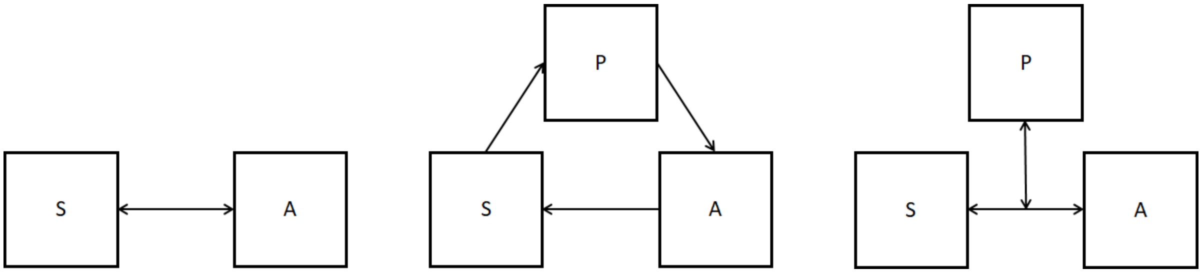

Fig. 1. Traditional Robot Architectures: (a) *Reactive* paradigm (S-A); (b) *Deliberative* paradigm (S-P-A); (c) *Hybrid* paradigm (P, S-A), with primitive functions such as S: Sense, A: Act, and P: Plan.

(SAMIR) able to successfully perform in real-world and real-time conditions.

The paper is structured as follows. In Section II, we present the proposed SAMI interactive robot architecture, while in Section III, we describe the automated pet use case application we have developed and embodied the SAMI architecture for. Conclusions are drawn up in Section IV.

## II. PROPOSED ROBOT ARCHITECTURE

The proposed SAMI Robot Architecture defines an abstract, organizational view of software and hardware modules that become a robot when implemented and that is characterized by the Sense-Act/Interact functions as schematised in Fig. 2. In the *Sense-Act-Modulated-by-Interactions* (SAMI) architecture, human-robot interactions could, on one hand, trigger the reactive control and, on the other hand, moderate it.

Thence, the SAMI-based robots have not only the properties of emergent behaviour due to the interplay between the robot's controller and the environment where the robot is placed, but also of interactive behaviour due to the interactions within the human-robot team, ranging from teleoperation to 'shoulder-to-shoulder' actions in unstructured environment.

In the SAMI architecture, the sense function is independent of the type of sensors which could be multi-modal and thus could take information based on the input from any of the five Aristotelian methods of perception known as the *five senses*, namely, the sight [23], [24], the hearing [25], [26], the touch [27], [28], the smell [29], and the taste [30].

The act function primarily takes the sensed information and produces the output commands for the robot's effectors such as wheels, manipulators (e.g. grips) and/or actuators like electric motors.

On the other hand, the interact function takes real-time information from the robot's teammate(s) and could thus modulate the sensor-driven output commands and/or trigger other output commands, i.e. HRI-driven ones. Hence, the motion of a SAMI mobile robot is not determined by a model-based deliberative planning, but is reactive to the sensors and even to the human-robot interactions. Furthermore, a SAMI robot makes reflex-based, low-level decisions as well as HRI high-level decisions in real time. The SAMI architecture allows thus to connect perception with action by combining both robot's reactive and interactive control, instead of using an automated planner; the resulting robot relying on its teammate rather than on any world model.

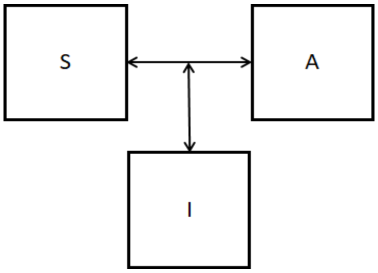

Fig. 2. Proposed SAMI Robot Architecture: *Interactive* paradigm (S-A/I), with primitive functions such as S: Sense, A: Act, and P: Plan.

SAMI robot architecture could support human-robot teamwork for a broad range of tasks. Indeed, the level and nature of interactions between a human and a SAMI-based robot could, on one hand, determine the degree of robot's autonomy, and on the other hand, set off robot's bio-inspired behaviours.

Moreover, the SAMI architecture is not limited to a specific structure or type of teammates, as it does not involve the robot's learning about any people models, decreasing thus any training phase, while increasing the adaptability of SAMI-embodied robots.

## III. VALIDATION AND DISCUSSION

To validate our proposed *Sensing-Acting-Modified-by-Interacting (SAMI)* robot architecture, we looked into robot pet applications we developed a use case for, as described in Section III-A. We implemented it and tested it, as explained in Sections III-B-III-C, respectively.

### A. Use Case

After the success of the digital, virtual pet *Tamagotchi*, the next step in automated pets has seen the arrival of robot pets such as the fur robot pup *Paro* [31], the sophisticated robot dog *Aibo* [32], or the zoomorphic robot turtle [33]. Robot pets are bio-inspired robots that could be used as toys, but also could be considered as companion robots which can socially interact with humans in an unstructured environment.

For this purpose, we have developed the *SAMI Robot Pet* use case applying the Use Case Template presented in [34], as follows:

- *Name*: *SAMI Robot Pet*
- *Identifier (optional)*: version 1
- *Author(s)*: J. I. Olszewska

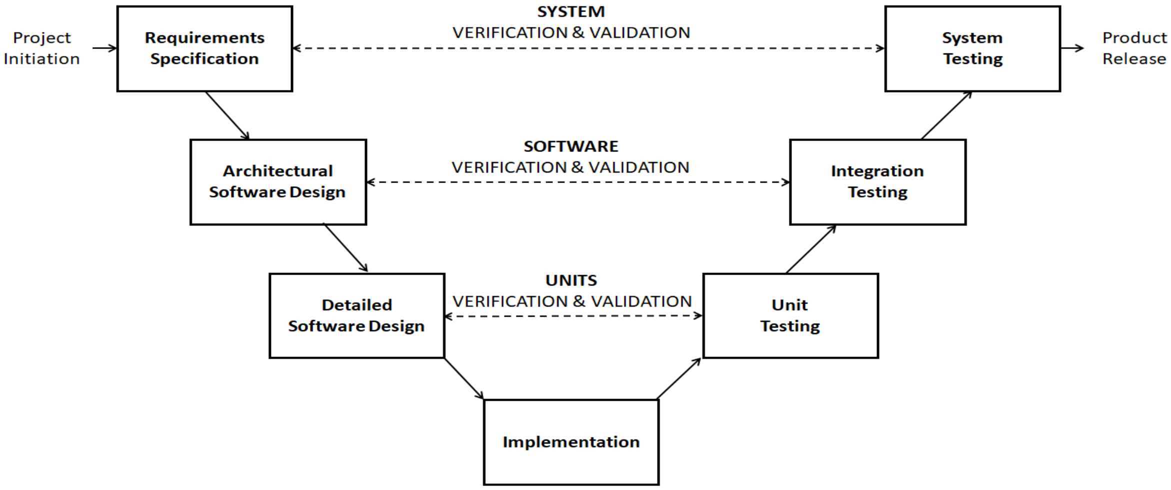

Fig. 3. Software development life-cycle V-model.

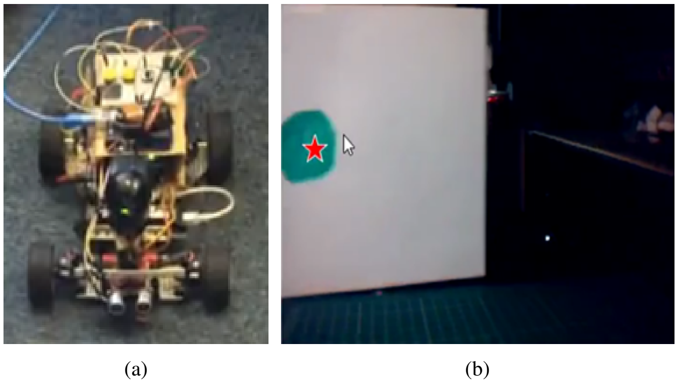

Fig. 4. Implementation results: (a) Developed SAMI-based Robot pet (SAMIR); (b) SAMIR's machine vision.

- *References*: [31], [32]
- *Context Description*: A companion robot pet and a person are interactively playing in real time and in a real-world, indoor environment; the mobile robot aiming to follow a colour-ball object the person is moving playfully in proximity.
- *Intent/Purpose*: This use case aims to serve as the basis to study some Human-Robot Interactions (HRI) and to illustrate a possible deployment of our SAMI architecture.
- *Preconditions*: We focus on the interactive aspect of the robot pet rather than on its zoomorphic aspect.
- *Scenario (aka Course of Action)*: To play together with people in real time and in an indoor space, the companion robot pet detects a coloured object (e.g. a green ball/green spot) handled by a person. The mobile robot interacts with the person by rotating accordingly to the object's direction, while the person is moving the object quickly and randomly.
- *Alternate Related Scenario (optional)*: When playing with people, the robot pet could move forwards and backwards based on the distance from the coloured object.
- *Postconditions*: The mobile robot stops playing with the person when the person decides it by keeping the object out of robot's range or by switching off the robot.
- *Relevant Knowledge*: {sense, act, interact}.

### B. Implementation

To build a robot pet such as described in our use case (Section III-A), we embodied the SAMI architecture introduced in Section II, applying the V-model depicted in Fig. 3.

While the high-level design of this SAMI-based Robot called SAMIR is following the architecture displayed in Fig. 2, its low-level design is presented in Fig. 4.

In order to meet the robot pet's requirements as specified in the use case (Section III-A), two among the five senses were implemented by embedding sound and vision sensors in the first prototype embodying SAMI architecture (see Fig. 4 (a)).

Indeed, machine vision is important for both robot's low-level perception [35] and high-level cognition [36], [37] as well as for human-robot interactions [38], whatever proximate interactions [39] or remote interactions, leading teleoperations/telerobotics [40]. On the other hand, sounds [26] and ultrasounds [41] are important for human-robot communication and interaction as well as for odometry.

Moreover for this use case, the SAMI embodiment is a mobile, wheeled robot, where the effectors (i.e. the four wheels) have a controllable steering system and DC motor control board.

Hence, as illustrated in Fig. 5, the SAMIR hardware set-up consists of a USB webcam 640x480 HID compliant (Sensor 1), an ultrasonic sensor HC SR04 (Sensor 2) with an operational range of 2m, and a 4-wheeled platform with two Arduino Uno boards, where one (Microcontroller 1) controls two Servo motors (Servo Motor 1 and Servo Motor 2) actioning robot's webcam rotation and front wheels' steering, respectively, and the other one (Microcontroller 2) controls two DC motors (DC Motor 1 and DC Motor 2) actioning robot's rear wheels.

The main SAMIR software units are the direction control unit and the drive control unit (Fig. 5). Their implementation has been done using MatLab and Arduino programming languages and using related IDEs, support packages and

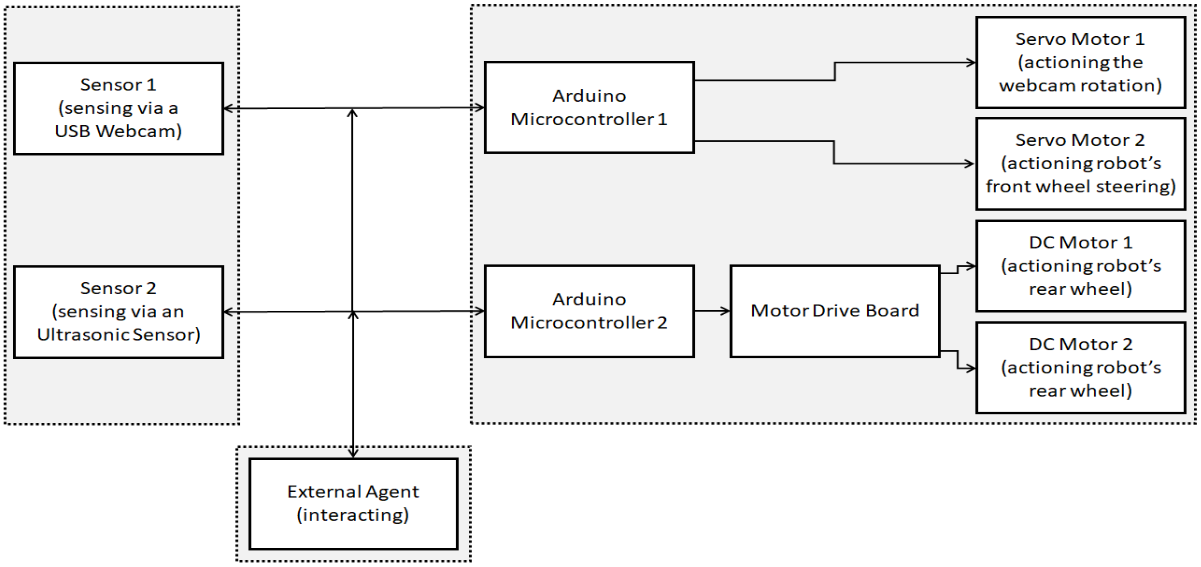

Fig. 5. SAMI-based robot architecture low-level design.

**Algorithm 1** Pseudocode for our direction control algorithm

```
Connect to Arduino
Create Servo objects
Connect to Webcam

Initiate Function to take an image snapshot on Webcam
Run the algorithm to locate the target object (if any)
if target object is detected then repeat
    repeat
        Find target object's location ($T_L$) on the image feed
        Read servo's current position ($S_P$)
        Run PD Loop($T_L$, $S_P$)
        Adjust the servo angle
    end ▷ The loop is interrupted when the user exits.
end if
```

**Algorithm 2** Pseudocode for our PD control algorithm

```
Given $T_L$, the target object's location on the image feed
Given $S_P$, the servo's current position
Given $M$, the middle section of the image

Error Value = $|M - T_L|$
PD value = (Kp constant * Error Value)
+ (Kd constant * (Error Value - Last Error Value))
Convert PD value to an acceptable amount

if $T_L$ is on the left side of the image then
    AngleValue=CurrentAngleValue-ConvertedPDValue
else
    if $T_L$ is within the middle range of the image then
        Angle Value = Current Angle Value
    else
        AngleValue=CurrentAngleValue+ConvertedPDValue
    end if
end if
if AngleValue < Minimum Allowed AngleValue then
    AngleValue = Minimum Allowed AngleValue
else
    if AngleValue > Maximum Allowed AngleValue then
        Angle Value = Maximum Allowed AngleValue
    end if
end if
return AngleValue
```

toolboxes such as MatLab image acquisition toolbox, MatLab webcam support package, and MatLab support package for Arduino hardware.

The direction control unit is responsible for half of the robot's system that controls the steering as well as the webcam's rotation angle. This is to ensure that the webcam always face the direction the robot is turning towards as per use case.

For this purpose, the servo motor has a proportional-derivative (PD) controller. Its response is to rotate at an angle varying with the coloured object's positions. Since applying a servo motor for the closed-loop control of the webcam rotation via an Arduino board that uses the MatLab program could introduce a latency that would affect servo responsiveness against target object's movement, appropriate values (e.g. 60Hz) should be set for the refresh rate and angular momentum of the servo.

Hence, when playing, SAMIR (Fig. 4 (a)) detects the coloured object from a webcam live video feed (Fig. 4 (b)), and can determine and acknowledge if the object is on the left or right of the webcam feed. This acknowledgement is used in conjunction with the Arduino 1 controlled servo to turn the webcam to face the target object when it moves towards the outer boundaries of the webcam on the horizontal axis (see Algorithms 1-2). It is worth noting that the left-right detection is based on pixel values and depends on the configuration of the webcam. So, the value that determines the boundary of the left-area could be set by means of a calculation that takes the input resolution and divides its horizontal value by the ratio required for the left-area width. A similar calibration could be done for the right area.

The drive control unit is responsible for the other half of the robot's system that controls the robot's speed and distance from the target object as per use-case alternate scenario. This unit was programmed using Arduino IDE. The program is then uploaded to the Arduino Microcontroller 2 and works as an independent unit. It is connected, on one hand, to the HC-SR04 ultrasonic sensor for input, and on the other hand, to a motor drive board (which controls the two DC motors) for output.

Hence, when playing, SAMIR moves forward or backward depending of the sensed distance between itself and the target object handled by the human teammate.

### C. Experiments

The developed SAMI-based robot (Section III-B) has been tested following the V-model (Fig. 3).

Prior to undertake any software test, all the hardware components such as the motors, etc. have been tested independently and were working correctly.

Next, experiments with a team consisting of the SAMIR robot (Fig. 4(a)) and a person, in context of the presented use case scenario and alternate scenario (Section III-A), have been carried out accordingly. Indeed, in these experiments, the SAMI-based robot is able to sense the target object, on one hand, through the webcam, and thus tracks the position of the colour detected object and acts in order to strive the robot's steering based on that (Figs. 6-7). On the other hand, SAMIR is able to sense the target object through the ultrasonic sensor, and consequently, computes the distance in between the target and the robot and then acts to move the robot's wheels forwards and backwards based on this sensed distance (Fig. 8). SAMIR's actions are modulated or result from the robot's interaction with a person which moves quickly and randomly a target object like a green ball spot.

Unit testing has been performed for all the robot's units. For example, in case of the main scenario, when the person places a coloured object (e.g. a green ball/spot) in front of the robot's webcam, the robot (Fig. 1(a)) correctly detects it and marks it with a red star as displayed in Fig. 4(b). SAMIR will automatically track this green object until the object is no longer visible. In case of the alternate scenario, e.g. when the person puts the target object at different distances in front of the robot's ultrasonic sensor, the robot's Arduino serial monitor reads the correct measure within the sensor range, i.e. up to 2m.

Integration testing has consisted mainly in testing the directional control and the speed control.

To test the speed control, the person place a target object at different distances in front of the robot's ultrasonic sensor and depending on that distance the robot moves successfully forward or backward (Fig. 8). For example, if the object is at 30cm from the robot, SAMIR moves forward until it is within a specific boundary value from the object. If the object is at 10cm from the robot, the car will move backward until it is within a specific boundary value from the object, e.g. 20cm.

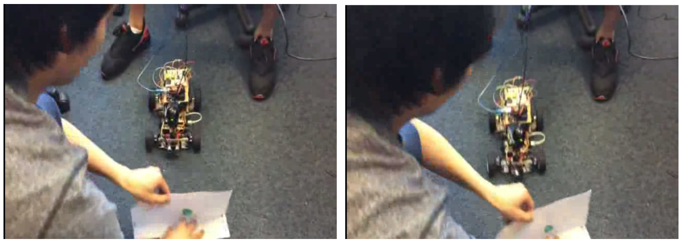

Fig. 6. Result samples of SAMIR robot left-rotation action.

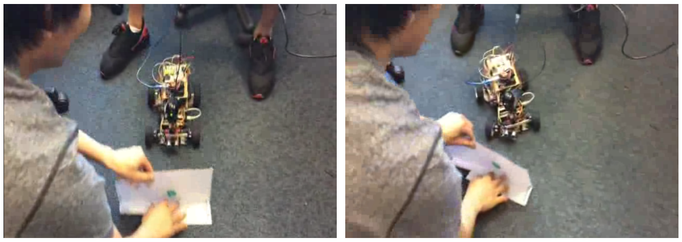

Fig. 7. Result samples of SAMIR robot right-rotation action.

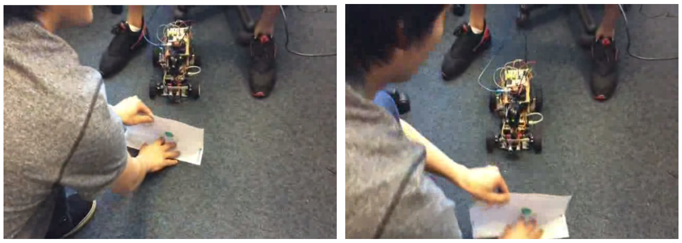

Fig. 8. Result samples of SAMIR robot forward/backward action.

To test the directional control, the person puts a colour object at a certain distance from the robot and moves it left (Fig. 6) and right (Fig. 7). The robot follows the target object left and right without any problem. Indeed, when the object is moving, the robot's webcam tracks it, trying to center it. When the person moves the colour object quickly, the robot is able to track this faster moving target object, but less smoothly.

For the system testing, further experiments for different values of the motor speed, PD values, and ultrasonic range have been carried out. An exemplary set of parameter values for robot's stable actions when interacting with the human and tracking the target object is as follows: motor speed = 70/255, $K_P$ = 0.11, $K_D$ = 0.08, and the ultrasonic distance range = [20cm-70cm], leading to SAMIR's successful response to varying speed and random movements of the target object in case of the presented human-robot interactive scenarios.

## IV. CONCLUSIONS

As companion robots and robotic services tend to be more and more present in our society, we presented in this paper the Sense-Act robot architecture Modulated by the potential Interactions (SAMI), well suited for human-robot interactive (HRI) applications. In particular, our SAMI robot architecture has been implemented for the case of a mobile, autonomous robot pet application and has shown excellent performance when tested in unconstrained, real-world and real-time conditions.

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