Towards Flexible Assistive Robots Using Artificial Intelligence

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Abstract. New generations of robotic systems capable of taking care of human-level tasks are becoming more and more desirable especially if considering the lack of human support in health-care assistance for the elderly. Assistive Robotics is a growing research field that is also applied to support both older adults and caregivers in a variety of situations and contexts. It leverages and integrates results from different research areas like e.g., Artificial Intelligence (AI), Cognitive Systems, Psychology and of course Robotics. Concerning AI, many of the technological skills that assistive robots could benefit of to achieve their objectives represent important challenges for that field. Some of the most relevant are the capability of monitoring and understanding information coming from the environment, the capability of interacting with humans in a flexible and *human-compliant* way, the capability of proactively performing supporting tasks inside the environment and also the capability of personalizing both interactions and services according to the specific needs of the assisted person. Thus, there are many techniques of AI that must be "integrated in a loop" to realize a needed set of advanced capabilities. This paper presents a research initiative which aims at realizing an enhanced (cognitive) control architecture to endow autonomous and socially interacting robots with a number of such advanced functionalities. Specifically, the paper presents an initial version of the envisaged control architecture, called KOaLa (Knowledge-based cOntinuous Loop) which integrates sensor data representation, knowledge reasoning and decision making functionalities.

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1 Introduction

Nowadays, there are many widely diffused commercial robotic solutions like e.g., robot vacuums or industrial lightweight robots, while a new generation of Intelligent Robots are entering our working and living environments, taking care of human-level tasks. Such robotic systems are becoming more and more important also in elderly healthcare assistance. Indeed, recent advancements in Artificial Intelligence (AI) and Robotics are fostering the diffusion of robotic agents with the capabilities needed to support both older adults and their caregivers in a variety of situations (e.g., in their homes, in hospitals, etc.). Such robotic agents must be capable of monitoring and understanding information coming from the environment, interacting with humans in a flexible and *human-compliant* way, autonomously performing tasks inside the environment and also personalizing interactions and services according to the specific needs of the assisted person.

The ability of representing and reasoning diverse kind of knowledge constitutes a key feature for allowing intelligent robotic assistants to *understand* the actual (and possibly time changing) needs of older persons as well as the status of the environment in which they are acting and inferring new knowledge to adapt their behaviors and better assist humans. The need of supporting long-term monitoring and deploying personalized services for different users opens to the exploitation of sensor networks to gather information about the status of the assisted persons and their living environments in order to figure out which is the actual situation and how effective assistance can be provided. New social robots are entering the market (e.g., Pepper by SoftBank Robotics) but they still lack advanced reasoning capabilities to provide well suited and effective impact in healthcare assistance, contributing in prolonging elderly independence as well as increasing their quality of life.

AI techniques constitute a key enabling technology for realizing adaptive assistive services to implement continuous monitoring and support daily-home living of seniors. This paper tries to identify the main requirements that an intelligent assistive robot must satisfy to realize effective services aimed at taking care of older adults inside their home living environment. According to this requirements we make an hypothesis concerning the main AI techniques that can contribute to achieve the desired objectives. We propose an advanced cognitive architecture integrating these AI techniques into a unified control loop and we discuss the related responsibilities and contributions with respect to the desired intelligent assistive behaviors. Then, we show a (partial) implementation of the envisaged cognitive architecture called KOaLa (*Knowledge-based cOntinuous Loop*) which has been designed by leveraging the results and the experience earned with GiraffPlus [8] (a research project funded by the European Commission representing a successful example o the use of AI in domestic care contexts).

2 Requirements for Daily-Home Assistance

The development of reliable AI and robotic technologies aimed at supporting the daily-home living of persons directly at home is a really challenging research objective. There are many heterogeneous situations such systems must properly deal with to effectively support a person and, therefore many features and capabilities must be taken into account. Taking inspiration from the experience in GraffPlus [8], it is possible to identify a set of key requirements characterizing the capabilities of intelligent assistive robotic systems. These requirements can be characterized according to four correlated perspectives: (i) environment perspective;

(ii) autonomy perspective; (iii) interaction perspective; (iv) adaptation perspective.

- **Environment perspective.** Pursuing the idea of GiraffPlus different types of sensor can be used to gather information about the environment and the health status of the assisted person. The number and the type of the sensors deployed into the environment depend on the specific purposes and objectives that must be achieved. Broadly speaking, there are two categories of sensing devices that are relevant in domestic assistance scenarios. Environmental sensors produce data about the state of a particular area of the house like e.g., the kitchen, the living-room and so on. Physiological sensors produce data about physiological parameters of a person like e.g., blood pressure, hearth rate and so on. Thus, IoT and sensing devices represent a precious source of information characterizing different features of a working context. The envisaged assistive robotic system must be capable of dealing with a continuous flow of heterogeneous data coming from sensors to monitor the state of the environment and autonomously recognize particular situations that require support. Namely, the system must be capable of recognizing activities the assisted person is performing inside the house as well as recognizing events related to the state of the house or the health of the assisted person.
- **Autonomy perspective.** Analyzing the knowledge gathered from the environment the envisaged system can recognize particular situations that may require to proactively execute supporting tasks. This means that a "causal knowledge" is needed to characterize the basic rules that enable a safe and correct interaction of the system with the environment. According to this knowledge, the system knows its internal capabilities and how they interact with the environment and therefore can autonomously decide the sequence of activities needed to achieve a desired objective like e.g., a supporting task. A decision making process is needed to achieve the level of autonomy needed to automatically synthesize and carry out supportive actions.
- **Interaction perspective.** The assistive robot must be capable of interacting with humans at different levels and with different modalities like e.g., gestures and/or voice. In general, the interactions between humans and robots must be as safe and "natural" as possible. Older adults should interact with an assistive robot in a "natural way" using a "natural language" and they should not feel the robot as an obstacle into the house and/or as a danger for their safety. To achieve this an assistive robot must correctly understand commands and instructions coming from humans and must show behaviors that are safe but also socially acceptable by humans. Namely, the behaviors of an assistive robot must comply with so-called social norms that are necessary to effectively take part to "social life". The work [3] represents an interesting contribution in this context considering the task of a robot serving some coffee to a patient. Even for a "simple task" like this a robot must comply with "social norms" in order to carry out the task in human-compliant way. Indeed, both cups and watering cans are capable of containing fluids and there-

fore coffe but, it would be strange (or not human-compliant) to serve coffe using a watering can.

- **Adaptation perspective.** Different persons have different habits and different needs that may also change over time. Assistive robots must tightly interact with persons during their daily-home living and therefore a general and "static behavior" would not be effective. An assistive robot must be capable of adapting its behaviors and interactions according to the specific needs of the particular assisted person. Namely, an assistive robot should be able to build profiles according to its experience and personalize its behaviors to different persons accordingly.

3 Conceptual AI^3 Architecture for Assistive Robots

The envisaged assistive robotic system must be capable of integrating a heterogeneous and complex set of (intelligent) capabilities. There are several techniques in AI that address some of the challenges raised by the requirements described above. Machine learning, knowledge representation and reasoning, automated planning and execution represent three well-established field of AI that can play a key role in this context. A proper integration of these techniques can endow an assistive robot with the capabilities needed to achieve the desired objectives. Thus, the long-term research objective we are pursuing aims at realizing an enhanced cognitive architecture for assistive robots integrating three core AI techniques.

Research in cognitive architecture aims at endowing an artificial agent with a hybrid set of cognitive capabilities that range from learning and perception to problem solving and acting. As stated in [13], research in cognitive architecture is important because it enables the creation and understanding of (synthetic) agents that support the same capabilities as humans by integrating results in cognitive sciences and AI. A key point in the design of cognitive architectures is the management of different source of knowledge and the basic capabilities needed to access and process such knowledge. For example, knowledge from environment comes through perception, knowledge about opportunities of a particular state of the environment comes through planning, reasoning and prediction. Many works in the literature have analyzed cognitive architecture [13, 15] and have introduced and applied systems based on cognitive architectures with interesting results. ACT-R [2, 1] SOAR [10, 11] and ICARUS [12] are just some examples of the most relevant cognitive systems realized in this field. Although not so recent, we take the work [13] as a reference for the design of our cognitive system. In our view, that work provides a good and complete discussion of the principal capabilities a cognitive system must be endowed with which is well suited for our purpose.

Figure 1 shows the elicited three-core architecture (AI^3) showing the main building blocks and their relationships within the control flow. The architecture is composed by three different layers encapsulating the three

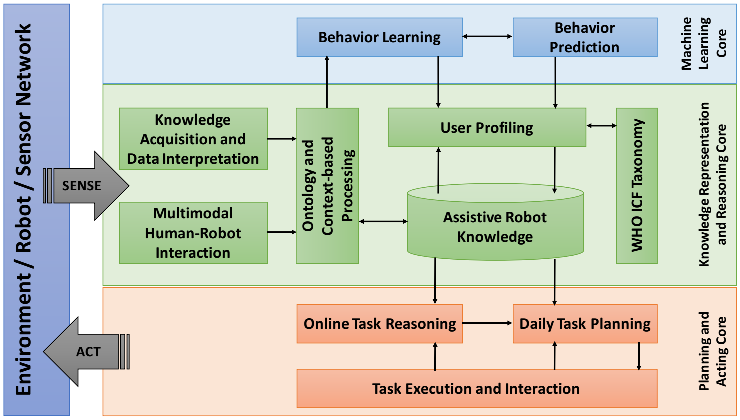

Fig. 1. The three-core-based conceptual architecture

AI techniques mentioned above. The *Knowledge Representation and Reasoning Core* is the part of the architecture responsible for processing information coming from the environment. There can be two types of information the system must deal with. Sensor data about the environment the system must properly acquire, interpret and contextualize. Human instructions and commands the system can receive by interacting with persons through different modalities (voice and gestures). The elements *Knowledge Acquisition and Data Interpretation* and *Multimodal Human-Robot Interaction* are responsible for dealing with these two different sources of information respectively. The information received from these two different "channels" must be processed in a uniform way, according to a well-defined semantics in order to extract useful knowledge. Specifically, the *Ontology and Context-based Processing* relies on an ontological approach to define a semantics guiding the interpretation of sensor data and the related processing mechanisms. Indeed, it defines a set of context-based rules used to process external data and extract knowledge about the events, activities and tasks that characterize the state of the environment and the assisted person. it enables a context-based knowledge processing mechanism which allows an assistive robot to continuously refine its internal knowledge, i.e., the element *Assistive Robot Knowledge* shown in Figure 1.

The knowledge generated by means of this processing mechanism is central to the (enhanced) control loop and *synchronizes* the three AI-cores composing the architecture. The *Machine Learning Core* is in charge of further enriching this knowledge by taking track of interactions and events to *learn* the particular needs of a specific person/patient and build a model of his/her possible behaviors. Broadly speaking it is possible to distinguish two basic elements. The *Behavior Learning* element is in charge of recognizing patterns or repetitive behaviors by analyzing stored information about interactions between the assistive robots and a patient as well as the activities of a patient inside the house. The *Behavior Pre-*

diction element is in charge of analayzing learned behaviors to build a suitable model of a patient and "predict" his/her possible activities and interactions accordingly. Such a model can be used to enrich the knowledge of the assistive robot and build a *profile* of a patient. The profile of a patient can also include a description of his/her health-related needs by leveraging a proper representation of the *ICF Taxonomy* made by WHO[1]. Leveraging all this information an assistive robot can build a quite rich model of a patient characterizing his/her health status as well as his/her behaviors inside the house.

The *Planning and Acting Core* is the part of the architecture responsible for actually interacting with the patient and the environment. It leverages the built knowledge of the assistive robot to characterize the operations that can be performed into the environment as well as the set of events and/or activities that can require support. Specifically, the *Online task reasoning* element is responsible for proactively identify tasks that must be executed according to the events and activities detected by knowledge processing mechanisms of the architecture as well as commands/instructions received by a patient. These tasks are integrated into the *Daily Task Planning* element which maintains the (temporal) plan of the supportive tasks planned within the day. The daily plan is synthesized by taking into account a (temporal) model of the assisted person characterizing his/her specific needs and behaviors. The tight integration of these two elements allow an assistive robot to dynamically adapt its behaviors and the executed supportive tasks according to the specific *profile* of the assisted person. Then, these tasks are executed by actually acting into the environment through a closed-loop control cycle which executes actions and receives feedbacks about their execution from the environment.

4 The KOaLa Cognitive Architecture

The AI^3 architecture elicited in Figure 1 represents a sort of roadmap for the challenging research objective we are pursuing within the KOaLa research initiative recently started. This initiative has been inspired by the successful results obtained with the GiraffPlus research project [8]. This project developed an integrated system composed by a sensor network and a telepresence robot aimed at supporting and monitoring the daily-home living of a senior person directly in his/her house. Several pilot studies were made during which a telepresence robot (the Giraff) was actually deployed in the house of people for several months [5]. Among these, particularly relevant is the case of "Nonna Lea" who represented an ideal and inspiring user for the project[2].

GiraffPlus envisages an application context consisting of a mobile telepresence robot capable of autonomously interact with an older person through audio/text messages and gestures [9] as well as navigate her living environment. The robot is also endowed with videoconferencing

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[1] http://www.who.int/classifications/icf/en/

[2] https://youtu.be/9pTPrA9nH6E

functionalities that allow the user to communicate with a caregiver in the "external world" (e.g., a relative or a doctor). The robot is supposed to move inside a sensorized environment that can produce data about the status of the house as well as the status and activities of the user. Thus, the control architecture of a GiraffPlus-like assistive robot must continuously process sensor data to understand the status of a person (according to his/her specific health-related needs) and the environment (the operative context) and, then dynamically synthesize the actions needed to better support the user.
Following the AI^3 architecture, the improvement introduced by KOaLa consists of the integration of a knowledge processing module, called the *KOaLa Semantic Module*, and a planning and execution module, called the *KOaLa Acting Module*. The integration of these two modules realizes an cognitive high-level control loop enhancing the capabilities of GiraffPlus. Fig. 2 shows a conceptual representation of the envisaged cognitive architecture and highlights the different phases of the *control flow* which starts with the gathering of data from the sensor network and ends with the execution of actions in the environment involving, e.g., the robot or sensor configurations.

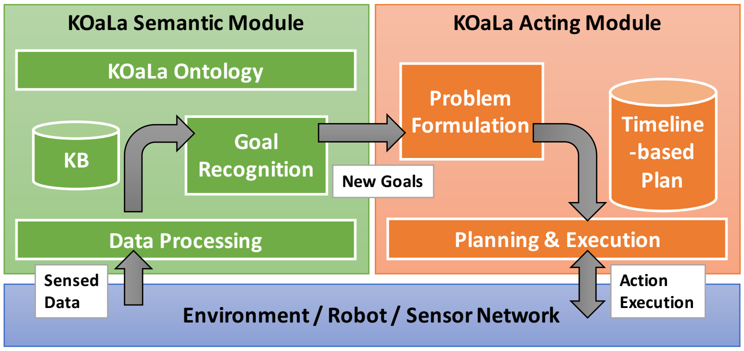

Fig. 2. Semantic and Acting modules of KOaLa *sense-reason-act* in details

4.1 The Semantic Module

The *KOaLa Semantic Module* is responsible for the interpretation of sensor network data and the management of the resulting *knowledge* of the robot. This module relies on the *KOaLa Ontology* to provide sensor data with semantics and incrementally build an abstract representation of the application context i.e., the *Knowledge Base* (KB). A *data processing mechanism* uses standard semantic technologies based on the Web Ontology Language (OWL) [4] to continuously refine the KB and infer additional knowledge (e.g., about user activities). Then, a *goal recognition process* analyzes the KB in order to identify specific *situations* that require a proactive "intervention" of the robot and dynamically generates related *goals* for the acting module.

The KOaLa Ontology The KOaLa ontology has been defined by leveraging SSN [7] and DUL[3], two stable and publicly available ontologies. The KOaLa ontology has been structured according to a context-based approach which characterizes the knowledge by taking into account different level of abstractions and perspectives. Specifically, three levels (i.e. contexts) have been identified: (i) the *sensor context*; (ii) the *environment context*; (iii) the *observation context*. The *sensor context* characterizes the knowledge about the sensing devices that compose a particular environment, their deployment and the properties they may observe. This context strictly relies on SSN by providing a more detailed representation of the different types of sensor that can compose an environment as well as the different types of property that can be observed. Leveraging this general knowledge, it is possible to dynamically recognize the actual monitoring capabilities as well as the set of *operations* that can be performed according to the types of sensor available and their deployment. The *environment context* characterizes the knowledge about the structure and physical elements that compose a home environment, and the deployment of sensors. This context models the different *physical objects* that may compose a *home environment*, their properties and the particular deployment of the sensors. Thus, this context provides a complete characterization of a domestic environment and the relate configuration of the sensor network. Finally, the *observation context* characterizes the knowledge about the *features* that can actually produce information in a give configuration as well as the *events* and the *activities* that can be observed through them. This context identifies the *observable features* of a domestic environment as the physical elements that are actually capable of producing information through the deployed sensors. Similarly, this context identifies the *observable properties* as the properties of the observable features that can be actually observed through the deployed sensors. In this way, the KB is capable of representing observations and processing/interpreting received data by taking into account the associated environmental information like e.g., the are of the house data comes from or the type of object data refers to.

Knowledge Processing Given the semantics defined by the KOaLa ontology, a knowledge processing mechanism elaborates sensor data to incrementally build a KB. The pipeline depicted in Fig. 3 shows the main steps of this knowledge processing mechanism. The pipeline is composed by a sequence of reasoning modules each of which elaborates data and the KB at a different level of abstraction (i.e., ontological context) by means of a dedicated set of *inference rules*. Such rules define a semantics to link different ontological contexts in order to incrementally abstract data and infer additional knowledge which is integrated into the KB.

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[3] http://www.loa-cnr.it/ontologies/DUL.owl

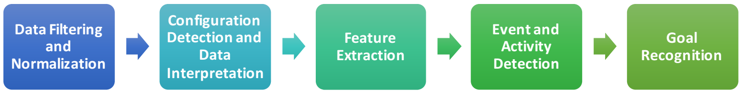

Fig. 3. Data processing pipeline for the knowledge inference and maintenance

The KB is initialized on a configuration specification which describes the structure of the domestic environment, the set of sensors available and their deployment. Then, the *Configuration Detection and Data Interpretation* module generates an initial KB by analyzing the configuration specification. Such initial KB is then refined by interpreting (filtered and normalized) sensor data coming from the environment. The *Feature Extraction* module identifies the observable features of the environment and the related properties. It processes sensor data in order to infer *observations* and refine the KB accordingly. Finally, the *Event and Activity Detection* module analyzes inferred observations by taking into account the knowledge about the environment. Different inference rules detect different types of events and activities according to the particular set of features and properties involved within the observations[4].

4.2 The Acting Module

The *KOaLa Acting Module* is responsible of planning and executing operations according to the events or activities inferred by the semantic module. These events are inferred by the *Goal Recognition* module (GR) of the knowledge processing pipeline show in Fig. 3. GR is a key element of the cognitive architecture because it provides the link between the semantic and the acting modules. Specifically, it leverages the inferred KB to connect knowledge representation with planning. It can be seen as a background process that monitors the updated KB in order to generate operations the GiraffPlus robot must perform. GR is the key feature of KOaLa to achieve *proactivity*. Operations that GR generates are modeled as *planning goals* the *problem formulation* process encodes into a planning problem specification. Such a problem specification is then given to a timeline-based planner which synthesizes a plan describing the sequences of operations needed to support the user. Thus, a *planning and execution* process leverages the timeline-based approach [6] and the PLATINUm framework [16] to continuously execute and refine the plan according to the input goals and the status of the execution.

Planning and Execution with PLATINUm The planning and execution capabilities of the acting module rely on a novel timeline-based framework, called PLATINUm [16]. PLATINUm complies with the formal characterization of the timeline-based approach proposed in

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[4] The knowledge processing mechanism has been developed by means of the Apache Jena software library (https://jena.apache.org/)

[6] which takes into account *temporal uncertainty*, and has been successfully applied in real-world manufacturing scenarios [14] recently. Broadly speaking, a timeline-based model is composed by a set of *state variables* describing the possible temporal behaviors of the domain features that are relevant from the control perspective. Each state variable specifies a set of *values* that represent the states or actions the related feature may assume or perform over time. Each *value* is associated with a *flexible duration* and a *controllability tag* which specifies whether the value is controllable or not. A *state transition function* specifies the valid temporal behaviors of a state variable by modeling the allowed sequences of values (i.e., the transitions between the values of a state variable). State variables model "local" constraints a planner must satisfy to generate valid temporal behaviors of single features of the domain i.e., valid *timelines.* it could be necessary to further constrain the behaviors of state variables in order to coordinate differente domain features and realize complex functionalities or achieve complex goals (e.g., perform assistive functionalities). A dedicated set of rules called *synchronization rules* model "global" constraints that a planner must satisfy to build a valid plan. Such rules can be used also to specify *planning goals.*
Given such a model, a PLATINUm planner synthesizes a set of timelines each of which represents an envelope of valid temporal behaviors of a particular state variable. These timelines allow the GiraffPlus robot to perform the desired assistive tasks. Then, an PLATINUm executive carries out the timelines by temporally instantiating the associated sequences of values, called *tokens.* Namely, an executive decides the exact *start time* of the tokens composing the timelines of the plan. In general, the actual execution of these tokens cannot be controlled by the executive which must dynamically adapt the plan according to the *feedbacks* received during execution. For example, the actual time the GiraffPlus robot needs to navigate the environment and reach a particular location cannot be decided by the planner or the executive. Indeed, the navigation can be slowed-down by obstacles and therefore the end and therefore the actual duration of a *navigation operation* is known only when the executive receives the associated execution feedback.

5 KOaLa in Action

Let us consider a typical assistive scenario consisting of older adult living alone in his/her single floor apartment composed by a living room, a kitchen, a bathroom, a bedroom and a central corridor connecting all the rooms with the entrance. There are many sensors that can be installed to track activities and events inside the house. Each window and the entrance door have been endowed with a sensor to check whether they are open or close. There is (at least) one sensor for each room to track temperature and luminosity and detect motions. Finally, there are additional sensors to track the usage of electronic devices like e.g., the TV, the oven or the microwave. In addition to these environmental sensors, there are other sensing devices that track physiological parameters of the assisted person like blood pressure, heart rate, glucose level, etc. All these sensing devices provide a rich and heterogeneous set of data the assistive robot can continuously analize through KOaLa to recognize activities the person is performing, or events/situations affecting the status of the house or the health of the person. Below there are some examples concerning typical situations we are focusing to inside the house during the daily-home living of a person in need of assistance. These examples show the objective of the enhanced assistive services:

- *The sensor network detects some activities in the kitchen of the house.* The information gathered from sensors is saying that *someone* is moving inside the kitchen, the TV is on, the luminosity is *high* and also that the temperature close to the flame is a bit higher than usual. Given this information and given the time, the assistive robot understands that “Nonna Lea” is *cooking* and therefore it plans to move towards the kitchen to remind the dietary restrictions she must follows. Then, the assistive robot plans to remind the patient to take his/her pills for the therapy in forty-five minutes which is the time she usually takes to complete the meal. In addition, the robot plans to send a message to her sons to ask them to call their mother in one hour and a half in order to check whether she has actually taken the pills or not.
- *The sensor network detects some activities in the living room of the house.* The information gathered from sensors is saying that *someone* is sitting on the sofa, the TV is on and that the luminosity of the room is *high*. According to these information the robot understands that the person is *watching the TV* and therefore it plans to move inside the living room and inform the person about the programming of the day. In addition, the robot notices that the person has neither made any calls to nor received calls from her sons today and therefore it plans to suggest to the person to call her sons before going to sleep.
- *The sensor network detects some activities in the bedroom of the house.* The information gathered from sensors is saying that *someone* is moving inside the bedroom and that the light inside the room is on. The robot checks the time and recognizes that it is the time at which the person usually goes to bed. However, it detects that the window inside the kitchen is open and that the light of the bathroom is on. Thus, the robot plans to move towards the bedroom in order to alert the person about the fact that the window must be closed and that the light in the bathroom must be turned off before going to bed. After a while, the information gathered from sensors in the bedroom says that *someone* is laying on the bed and that the luminosity of the room is *low*. The robot understands that the person is *sleeping* and decides to notify her sons about this. In addition, the robot notices that the temperature inside the bedroom is a bit higher than the *ideal temperature* for a good sleep. Thus, it decides to cool down a bit the temperature of the room by *controlling* either the air-conditioner or the heater according to season. The day after, the robot detects that the person is still *sleeping* at the typical time she wakes up. Thus, the robot plans to send a message to her sons about this unusual behavior within thirty minutes if she does not wake up before.

Such scenarios show ordinary life situations of a senior person and some roles that an assistive robot, with the help of KOaLa, can play to support her living at home. In particular, these scenarios show that KOaLa, through the combination of simple inference rules like e.g., *someone is moving inside the kitchen* and *the temperature close to the flame is higher then usual*, can endow a telepresence robot with the capability of autonomously reasoning on the state of the environment, inferring *complex* situations and dynamically triggering *goals* accordingly. A first set of inference rules has been developed to realize a "stratified" reasoning mechanisms capable of abstracting sensor data and inferring events situations concerning the status of the environment. Currently an extended set of rules is under development to realize the *goal triggering* mechanism needed to proactively link knowledge reasoning to planning and acting.

6 Conclusions and Future Works

This paper presented an AI-based cognitive architecture which integrates sensing, knowledge representation and automated planning techniques to constitute a high-level control loop to enhance proactivity features of an assistive robot designed to support an older persons living at home in her daily routine. A semantic module leverages a dedicated ontology to build a KB by properly processing data collected by means of a sensor network installed in the environment. An acting module takes advantage of the timeline-based planning approach to control robot behaviors. A goal triggering process acts as a bridge between the two modules and provides the key enabling feature to endow the robot with suitable proactivity levels. At this stage, some tests have been performed to show the feasibility of the approach. Further work is ongoing to enable more extensive integrated laboratory tests to better assess performance and capabilities of the overall system. Future work will also investigate the opportunity to integrate machine learning techniques to better adapt the behavior of the assistive robot to specific *daily behaviors* of different targeted people.

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