Situation Awareness in Autonomous Service Robots

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Abstract

Despite the increasing demand for service robots, considerable challenges remain to be solved before these robots can be ubiquitously employed in personal households. To this date, autonomously operating robots lack the flexibility to react appropriately in unforeseen situations. At the Human Factors Institute of the Universität der Bundeswehr München, a multi-disciplinary research group of psychologists, engineers and computer scientists aims to ascertain to which extent cognitive models of situation awareness may enhance a robot’s ability to display adaptive behaviour in unforeseen situations.

Introduction

In 2011, about 2.5 million robots were sold for personal and domestic use (International Federation of Robotics, 2012). The International Federation of Robotics projects sales of over 15 million units for the period 2012 to 2015 with experts indicating that service robots have an innovation and market potential similar to that currently presented by industrial robots (Decker, et al., 2011). To this date, autonomously operating robots lack the flexibility to react appropriately in unforeseen situations as important perceptual and decision-making structures are still designed by programmers before the robot begins its task. This leads to fragmented abilities and brittle performance, in particular in unstructured and dynamic environments, which are prevalent in domestic contexts (Benjamin, Monaco, Lin, Funk, & Lyons, 2012). Hence, perhaps the greatest challenge in the engineering of autonomously operating robotic systems remains the instillation of flexibility in the robot’s decision-making processes that would allow it to adapt to the demands presented by a dynamically changing environment at any given moment, whilst still pursuing a particular operative goal (as opposed to purely reflexive systems). This line of research can be subsumed under the label of cognitive robotics.

In an effort to tackle this problem of failing adaptability in robots, several approaches have surfaced in the different scientific disciplines that are currently active in the field of cognitive robotics. One school of thought, which derived from the computer sciences, focuses primarily on the effective harnessing of computational processing capabilities and the development of mathematical algorithms to create learning and hence adaptable systems. Within the paradigm of

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machine learning, numerous attempts were made to develop heuristics based on statistical properties of sensor signals and reinforcement learning in an effort to reduce processing time and computational power requirements that would lead to slow response times and likely ineffective behaviour in dynamically changing situations (e.g. Bagnell, Bradley, Silver, Sofman, & Stentz, 2010; Peters, Morimoto, & Tedrake, 2009; Bratko, 2010). Although considerable progress has been made in this domain in recent years, real-time learning and in particular adaptive behavior of robots in unforeseen situations remain a great challenge in robotics (Benjamin, Monaco, Lin, Funk, & Lyons, 2012). A different approach may be sought to complement these efforts. Cognitive scientists have tackled the issue of system adaptability by investigating human cognitive abilities that lead to adaptive behavior in such situations. Based on decades of experimental psychological work, numerous models have been proposed in this domain that specify human cognitive processes in dynamic situations (e.g. Baumann & Krems, 2009; Gonzales & Dutt, 2007; Durso & Sethumadhavan, 2008). As of yet, however, the evaluation of these cognitive models remains chiefly theoretical work; to our knowledge, a truly cognitive architecture has not yet been implemented in a robotic system (Benjamin, Monaco, Lin, Funk, & Lyons, 2012). Consequently, it is not sufficiently clear to which extent relevant models of human cognitive processes may be applicable to autonomously operating robots and improve performance of such systems. Systematic investigations of the issues which would surface in the implementation of such models in robots, are hence urgently required.

Situation awareness as a pivotal cognitive process in dynamic environments

Cognitive researchers have suggested that the basis for humans’ decision-making ability in dynamic situations forms their situation awareness (SA), a psychological construct which has withstood the scrutiny of several decades of empirical research. A commonly accepted definition of situation awareness has been proposed by Endsley (Endsley M., 1995, p. 36): „Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.“ Endsley further specifies situation awareness to occur at three consecutive stages, which are contingent upon the successful interplay of three key cognitive components: attention, working memory (WM) and long-term memory (LTM) (s. Figure 1).

The first step in achieving SA is the perception of status, attributes, and dynamics of goal-relevant stimuli in the environment. These are only perceived a) if the physical characteristics of these stimuli capture the human’s attention (bottom-up processing) and/or b) if they are focused upon and determined to be relevant as indicated by operative goals that are stored in the WM and LTM (top-down processing).
In a second step towards achieving SA, perceived stimuli are synthesized and associated with operative goals in the WM, which have been retrieved from a larger number of goals stored in LTM. Hereby, the WM allows one to modify attention deployment on the basis of other perceived information or a change in active goals (Braune & Trollip, 1982). The goal-dependent synthesis of information stored in the WM leads to a comprehension of the current situation and the stimuli’s relative significance in terms of achieving the goals.

In the third and final step towards achieving SA, future states of the elements in the environment may be projected based on the comprehension of the situation, leading to a timely and effective decision. For this purpose, a situation model which was created in the previous steps is stored in LTM and matched to schemata in memory that depict prototypical situations or states of the system model, which may be linked with goals that dictate further decision-making and actions. Hence SA equips the human agent with the ability to react appropriately in dynamic systems. In fact, numerous studies found a link between SA and effective performance (e.g. Gaba, Howard, & Small, 1995; Ma & Kaber, 2007; Gugerty & Tirre, 1996; Golightly, Wilson, Lowe, & Sharples, 2010).

**Project SAAROS: Situation Awareness in Autonomous Service Robots**

The aim of the proposed research program is to make a substantial theoretical and practical contribution towards improving the decision-making flexibility and hence adaptability of autonomously operating service robots using a distinctly interdisciplinary approach. To this end, a three-pronged approach is taken. Firstly, empirical data are gathered that reflect human processing of sensory input in the development of situation awareness, a cognitive process that was identified as pivotal to achieving adaptive behavior in dynamic situations. Secondly, a computational cognitive model which reflects these mechanisms is developed, using ACT-R, a cognitive architecture which was identified as featuring all necessary properties for the simulation of situation awareness (empirically supported cognitive plausibility, appropriate learning mechanisms). Thirdly, the cogni-
tive model is implemented in an autonomously operating NAO Next Gen robot (by Aldebaran) and evaluated for several scenarios that are relevant to service robotics and consequently adapted in order to reflect human-like adaptive behavior in dynamic environments. In the process of validating the developed model, systemic as well as structural influences which impact situation awareness in robotic systems are to be empirically uncovered and systematically documented. The following section details the working program of the Project SAAROS.

**Step 1: Identification of testing parameters**

First, two benchmark scenarios and appropriate experimental setups within the domain of service robotics are defined, which serve to validate a computational SA model with experimental data collected from human participants and which may be juxtaposed with data provided by a cognitively equipped NAO robot in later stages of the project. Specifically, the first scenario is required for the development and validation of the SA model in a particular task domain of service robots (Step 6). A second scenario is devised at this stage, which will serve to evaluate the extent to which the developed model generalizes to other task domains within the field of service robotics (Step 7). For both scenarios, performance goals are specified that determine the aimed level of functionality for the robot once it is equipped with a validated cognitive model of SA.

**Step 2: Formulation of an ACT-R model of SA**

A cognitively plausible ACT-R model of SA is formulated for the chosen context. In order to formulate an SA model within a cognitive architecture, the investigated scenario first needs to be deconstructed to its lowest operative level. For this purpose, the scenario is analyzed using goal-directed task analysis (GDTA), as proposed by Endsley (Endsley M. R., 1993). GDTA is a specific form of cognitive task analysis that focuses on identifying the goals and critical information needs for a particular task context. In essence, the product of this analysis is a hierarchy that specifically outlines the processes in which basic data needed by the user are integrated into higher SA levels of comprehension and projection. Second, based on the task analysis, an ACT-R model of SA is formulated.

**Step 3: Acquisition of experimental data & model validation for human data**

Following the GDTA (Step2), the model validation will occur in two stages, which are iteratively repeated until the model is considered to reflect human cognitive processes involved in SA satisfactorily: In a first step, the model is tested with regard to achievement and disruption of SA in humans. This includes experimental analysis with an opportunity sample of naïve participants. To measure the different levels of SA, a combination of tools will be used. Participants’ visual focus of attention can be tracked using eye-tracking and motion tracking. The SA levels of comprehension and projection are assessed with two
measurement techniques that have proven reliable and valid measures in numerous applications: SAGAT (Situation Awareness Global Assessment Technique) and SPAM (Situation Present Assessment Measure). With SAGAT (Endley, 1995), participants are intermittently queried, in the middle of a dynamic simulation, about the values of various parameters, whilst they are deprived of any feedback of the scene, so that the participant must rely on working memory to answer the questions. SPAM (Durso, Rawson, & Girotto, 2007) assesses the speed of accessing information while the scenario continues, so that the participant could seek the needed information rather than relying on memory. The SA measure, in this case is the time to respond. Statistical analyses will be conducted with quantitative measures in order to ascertain their degree of generalizability.

The formulated predictions are also tested with the ACT-R model. Functionally equivalent measures to those used with humans (eye-tracking, SPAM, SAGAT) can be applied to the measurement of SA in the ACT-R model: Visual focus of attention can be tracked and recorded during the programme’s run-time. In addition, response times and various task performance indices and buffer content (i.e. working memory content) can be assessed. In addition, behavioural trends can be discerned with the ACT-R simulations. Upon conclusion of the analysis of the model’s results, the ACT-R mechanisms may need to be adjusted and the hypotheses redefined. Hence, the testing process continues with stage (a) until the model achieves satisfactory performance (defined as overall model fit in performance measures of R=.7 or higher and comparable behavioural tendencies).

Step 4: Development of NAO/ACT-R Interface

Development work needs to be invested in order to equip an autonomously operating NAO robot, with an ACT-R model of SA. The higher level controls of NAO are realized by an embedded PC board in the robot’s head, which runs on a LINUX operating system. Aldebaran provides an SDK-Toolkit called NAOqi which provides an interface to the hardware on low and high level bases, supporting different programming languages, including C/C++ and Python. ACT-R, on the other hand, is composed of a set of functions and algorithms implemented in Common Lisp, which is not supported by NAOqi. Hence, an interface will be devised for the robot, which enables the communication of the robot’s controls with the perceptual-motor modules provided by ACT-R, for example, with use of CL Python, which is an open-source implementation of Python written in Common Lisp.

Step 5: Operationalisation of symbolic language with operative terms

With respect to the examined scenario and the results of the GDTA, operative terms need to be defined which translate the symbolic output of ACT-R into appropriate actions of the NAO robot and vice versa. This work package hence comprises two stages: Based on the GDTA (Step 2), a database is established
which contains detailed instructions for the robot for each symbolism specified in the ACT-R SA model. For example, if ACT-R determines during its run-time that the robot should “scan for next visual cue”, a corresponding translation is defined for the robot’s control and sensory processors, e.g. specifying the degrees of rotation of the robot’s head, the area in which it scans and a choice of target stimuli. The second step involves the implementation of an interface linking the robot’s API with an external PC on which the database is implemented. The decision to outsource this database was made to maintain fast run-times and at the same time ensure cognitive plausibility by considering these as subconscious processes, as humans do not, for example, consciously deliberate the degree to which they rotate their heads when they want to focus on an object of interest.

**Step 6: Validation of ACT-R model in the NAO robot**

Once the ACT-R model of SA developed in Step 2 has been validated with regard to human data and the model’s symbolic language has been translated into operative terms for the robot, the model can be validated in the NAO robot. For this purpose, the hypotheses that were established during the model validation process (Step 3) are investigated with the NAO robot using comparable measures of SA to those described in Step 3. The model is considered valid for the presented scenario if it achieves satisfactory performance (defined as overall model fit in performance measures of R=.7 or higher and the display of comparable behavioural tendencies). If the model does not display satisfactory validity, possible causes are identified and the model and/or physical setup may be adjusted accordingly.

**Step 7: Assessment of the model’s ability to generalize to other task domains**

In a final step, the extent to which the implemented model is task-specific is evaluated. For this purpose, the embodied ACT-R model is tested in a different test setup previously defined in Step 1, that requires the same basic skill set, but different reactions than the first scenario. From this final evaluation, systemic parameters may be delineated that can be identified as affecting SA in autonomously operating robots.

**Conclusion**

The multi-disciplinary project SAAROS at the Universität der Bundeswehr München can make contributions to three different domains: the empirical research on situation awareness in humans, the computational modeling of situation awareness using a cognitive architecture, and the embodiment of cognitive architectures in a robotic platform. Further investigations are planned to systematically assess the extent to which human cognitive processes may be applied to autonomously operating robots in order to produce adaptive behaviour in unforeseen situations.
References


