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# Action planning model for autonomous mobile robots

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***Abstract*—The main challenge for autonomous mobile robots is to interpret a new situation correctly and to react appropriately in unknown environments. Autonomous mission completion in new territory requires flexible, adaptable, complex, but also fast action planning. For most applications behavior selection cannot be simply rule-based, requiring more sophisticated evaluation systems delivering appropriate information and interpretation. This approach shows a solution using three control systems of different complexity, time lines and flexibility. One of the key modules of the behavioral software architecture schedules competitive actions proposed by the different control systems. The design has been tested in simulation, where mobile robots armed with different behavioral software models can compete in different game-like situations. The simulation has shown that cooperation between agents emerges to accomplish different situations.**

## I. INTRODUCTION

Robotics has gone through tremendous changes since its introduction about 50 years ago. First generations of robots were programmable machines, placed in factory lines to assist humans. Bound to narrow work cells, these robots were facing limited degrees of freedom of movement and almost no mobility. With the improvement in technology, robots started to learn how to move: To roll on wheels, to walk, to climb, to swim in order to navigate, to forage and to transport objects, and therefore to explore new working spaces. With the mobility of robots new challenges arose. The resources in area, energy, and computational capacity are limited on a mobile system, while requirements on behavior have increased dramatically. Separated from their automation background, mobile robots had to face new challenges in more unpredictable situations in a continuously changing environment right from the start. This dilemma was not so pronounced as long as the working space was placed in a factory site, where the environmental difficulties could be decreased by adjusting a well-defined and limited area for operation, but as soon as robots are situated in environments that cannot be adapted to their needs, new concepts become inevitable. As robots have started to provide services in the domestic area, new demands arise due to a more complex and unpredictable environment than is given in a factory or outdoor area, facing e.g. constrictions in moving in narrow passages and staircases, or rooms packed tightly with different forms of furniture representing all kinds of mobile and immobile obstacles. Efficient autonomous behavior, depending only on the sensory and processing units onboard, is a necessity to complete missions without external help in overcoming unpredictable problems and implications during the mission. Going beyond the domain of predefined tasks, new general purpose behavior architectures widen the usage of mobile robots with multifunctional designs for service and industrial domains, turning modern robots into assistants rather than tools, which can cooperate with humans rather than being directed by humans. Cooperation with (often untrained) human operators in shared tasks also entails responsibility requiring additional safety aspects avoiding dangerous robotic structures and behaviors. In order to create more and more sophisticated, autonomous, self organizing teams of robots, the main concerns after teaching robots how to move are now to decide what kinds of mechanisms are necessary to make them think independently and understand the environment they are situated in.

Artificial Intelligence (AI) has already dealt with the idea of emulating capabilities of the human mind for a number of decades. Often related to a rationalistic perspective encouraging the idea that the world can be described objectively, traditional AI concepts show major behavioral flaws in highly dynamic and unpredictable environments. Ironically, the psychoanalytic perspective, which is thought to give a deep insight into the human mind, has rarely been consulted in the debate about creating artificial intelligent behavior. The reasons for this dilemma are on the one hand the variety of often contradictory models in this subject and the "unscientific" image of psychoanalysis on the other hand, which seems to be an unfortunate prejudice [1]. Recent developments in psychoanalysis and cognitive science, giving a further insight into the mechanisms of the mind, draw a more unified and comprehensive picture of the human mind now. Turning from psychoanalysis to the sub-category psychodynamics, following general assumptions for a technological analogy in this approach [1]

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become apparent:

- The existence and crucial need of unconscious processes
- The fundamental role of conflicts and inhibitory mechanisms of mental processes

This paper emphasizes action planning and conflict resolution on the basis of contradictory action selection of multiple control systems. Furthermore, it describes the used test environments for evaluation and highlights the important values.

## II. PRELIMINARY WORK

The first behavioral architecture was proposed by a group of researchers under the direction of Prof. D. Dietrich (Vienna University of Technology) in 2003: Artificial Recognition System (ARS) is a successor of the first project called Smart Kitchen (SmaKi), intending to enhance automation control with methods of human perception and situation recognition for building automation [2] using further neuro-bionic concepts [3]. As control networks are very limited in their operation range, the introduction of autonomous mobile robots was a corollary of the task. This interdisciplinary method of resolution entailed major consequences resulting in a new behavioral architecture for mobile robots, introduced in [4] for the first time. The main concern in autonomous task allocation and decomposition lies in the fact that several tasks are more of an implicit rather than of an explicit character as the majority is derived from other demands. Therefore, a general concept for evaluating the current situation has become necessary.

Currently, two independent in-field projects are running, using the concepts of this research: Project SEAL is concerned with the equipment of rooms in a nursing home with different smart sensors to detect possible dangerous situations for elderly people. Project SENSE focuses on discovering abnormal situations at an airport, mainly using video cameras and microphones as sensor devices for a civil security monitoring system.

## III. BEHAVIOR ARCHITECTURE

Due to the interdisciplinary character of this approach, a consensus about crucial terms and technological relevance is highly desirable. Therefore, a short introduction to the basic terminology shall precede a description of the behavioral model.

*Image:* An image represents a kind of snapshot, describing the current relation of the agents (robots) to the environment, providing the momentary essential data about the current state of the system and the accurate description of the environment in the context of the next few steps of action planning. In general, images can be divided into two major categories [6]: Perceptual and mental images. The former represent the current state of the environment or the system's internal state. They are generated by sensing and evaluating processes. Mental images represent replications of historical data, e.g. events that are related to the current situation. They do not originate directly from perceptive processes, but from further mental processing. They are the basis of developing action plans, representing substantial replications of patterns once they have been experienced.

*Episode:* Perceptual images, as defined previously, cannot give direct information about developments. Only a coherent sequence of images can record observable changes and events in the environment or within the system, which is necessary for decision making. In cognitive science, the term "episode" is not explicitly defined, although the term "episodic memory" can be found in the literature, e.g. [5]. According to the definition of images, two different types of episodes are possible in our approach: *A perceptual episode* is the sequence of at least two different perceptual images. It describes the changes (differences) between these two abstract images on a coherent time line. *A mental episode* is a stored template or pattern of a group of similar episodes. It defines a sequence of abstract states caused by mental images. Mental images can be part of more than one mental episode, which gives a unique direction for transition.

*Emotion*: According to M. Solms [5], an emotion is a type of internally directed sensory modality that gives information about the current physical state as opposed to the state of the object world. A. Damasio [6] sees in emotions mental evaluation processes, which do not solely affect the physiological balance, but cause mental changes themselves. In general, emotions are classified in numerous complex emotions derived from the class of fundamental (basic) emotions. Unfortunately, there is no unified description of the number and function of basic emotions in psychoanalysis. Founded on neurological examination, [6] gives therefore evidence of their physiological existence besides observable external manifestations. According to [7], there are four primary emotional control systems: Besides the PANIC-, RAGE-, and FEAR-system that shall not be described in detail here, the SEEKING-system has a special functionality, as its objective is to assure the balance of the internal states of an organism. In technical terms, these basic control systems deliver fundamental decision tendencies – comparable with human reflexes – limiting the group of possible actions. Emotion control affects the number and types of images that are currently used, and it can also directly invoke short-term action primitives, which might be contradictory to long-term desire plans. Nevertheless, these action primitives can be inhibited by higher control systems if this serves the main goal.

*Desire:* In psychoanalysis, a desire is clearly assigned to the ID, the conscious part of the human psyche that tries to satisfy individual needs. It is a need to repeat a once experienced, internal satisfaction that fulfills an arising need as described in [9]. A desire is influenced by drives, recognized episodes, and emotions. It is triggered by an object of desire that can be either a physical object of the real world or a symbolic or abstract value, e.g. social acceptance. The desire can suppress drives or inhibit corresponding actions, which would be carried out under normal circumstances. The focus of attention during an active desire emphasizes those perceptions or actions that are relevant to satisfy the desire and to fulfill the corresponding needs.

### A. *Main functional blocks*

The behavioral architecture as proposed in [4] shows a number of key features, which have been emphasized and tested in recent developments. The main innovations are:

- The emotional evaluation that allow interpretations of new situations and scenarios for pre-decision, directly invoking action plans and action patterns.
- The concept of desire plans to reach long-term goals (missions) autonomously while allocating problems and constraints without external intervention.
- Parallel high-level and basic control systems, advising contradictory action patterns in the current situation, entailing a sophisticated concept of post-action selection, managing the limited resources of the robot to maintain coherent action sequences.
- Different types of long-term memories, containing images, episodes, semantic information, and a working memory that contains accurate data of images, desires plans, etc. for current processing.

### B. *Scenarios and desire plans*

As defined in chapter III, mental episodes are templates that represent a sequence of perceived images. By recognizing a complete mental episode, the agent becomes aware of the scenario in which it is currently placed in. The quality of awareness depends on the precision with which these templates are predefined.
To evoke a desire within an autonomous agent we took the psychoanalytical structure of a desire, which is described above as an implementation archetype. According to the object of desire, the desire is triggered when a specific mental episode is recognized, meaning that the agent is aware of a specific scenario. This episode can include external sensory input (e.g. vision) as well as intrasystem data (e.g. energy level).
The main part of a desire is the corresponding action plan. The individual agent knows what actions must be taken or what events must occur to reach the goal of fulfilling the desire. Fig. 1 shows a basic structure of the desire including a generic action plan (A-B-C-D) that leads to its satisfaction. The desire is initiated with the initial state, and within each state the following values can be defined:

- Probability of success
- Timeout for fallback to the last state
- Complex emotion values

The probability of success indicates the status of the desire. At the initial state, the probability is 0%, because no action has been taken to achieve the satisfaction of the desire. The probability of success increases with the number of reached states. This probability is defined for each state, thus there is no necessity for a linear interrelationship between

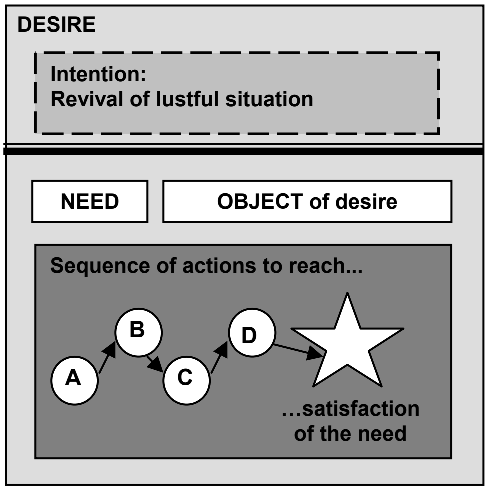

Fig. 1: Structure of desires

the number of reached states and the probability. The last state indicates that the desire has been fulfilled; its probability is 100%.
Within each state ($S$), a time to fallback ($\Delta t_{max}$) to the prior state ($S_n$) can be deposited. When a desire is in a specific state and the necessary transition condition (that can either be a perceived image or the completion of an action) to achieve the next state is not met, the state of the desire is cancelled and the last state becomes the current state again.

$$if\,(\Delta t > t_{\max}) \rightarrow S_n = S_{n-1} \quad (1)$$

With this concept, different possible ways of fulfilling a desire can be realized. If one plan does not work properly, another one will be chosen. For example in the case of environmental changes (new object of desire) affecting pre-conditions for initializing scenarios, other strategies might appear more appropriate. Exemplary scenarios are described in detail in [8]. This behavior model provides conditional abortion and inhibition of desires. Therefore, an abort condition and one or more transition conditions can be defined for each state. In addition to a transition of an episode, which is a solely passive action, the transition of a desire can also be a completed action. The described implementation architecture covers the whole specification of the psychoanalytically defined *desire* except for two items: evoking emotions and suppressing drive.
Therefore, each state can include one or more complex emotions. For example, if an agent reaches the 3rd state and for this state the complex emotion “HOPE” is defined, the desire registers an emotional value for the singleton object of the complex emotion “HOPE”. The object holds a list of emotional values that have an influence on the complex emotion. Thus, it is possible that different active desires can influence the same complex emotion, as shown in Fig. 2. If the state of the desire changes (this can be done by a step into the next or last state or by discarding the desire), the complex emotion value is unregistered and the same procedure is carried out within the actual state.

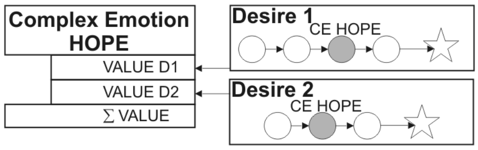


Fig. 2: Desires influencing the complex emotion hope

Each complex emotion state definition can be deposited with additional drive values. A positive value amplifies the perception of a drive, a negative value suppresses it. As a human tends e.g. to forget that he or she is hungry while being fascinated by new impressions, a similar concept can be used in the implementation of autonomous agents.

Section V shows the application of desires within the decision unit of an autonomous agent in a simulated test environment.

### *C. Memories*

Besides a general semantic memory containing general knowledge, [5] emphasized the episodic memory (EM) enabling autonomous agents to select actions by recalling previously made experiences. EM contains all agent-specific (autobiographical), experienced episodes aligned with their emotional rating. An episode is a sequence of perceived images that represents a concrete realization of a mental episode. The EM provides the agent with the ability to predict possible future sequences of situations or to anticipate the impact of specific behaviors. Combined with semantic rules the memory system can be used for abilities like localization and foraging, orientating, exploiting, or recognizing known structures (e.g. objects like furniture) in new environments (habitations).

Using concepts of E. Tulving [10] and A. Baddeley [11], an event-based approach is used to trigger the encoding of an experience. A currently recognized situation with relevant changes is recorded as an event (refers to an image) if it is supposed to have an impact on the agent, e.g. the change of the agent's internal state, which can be indicated by drives and emotions, the recognition of a significant change of the external perception, or a change of its behavior defined by its actions. The encoded events are rated with an emotional tone and a salience level. If the new episode exhibits major differences to existing (stored) episodic templates, the sequence of events within the realization of this episode-pattern is recorded as a new episode. Based on application-dependent estimation, e.g. the emotional impact, a new episode is classified as derivation of an existing template or as a novel experience. Various episodes represent an individual interpretation of a specific mental episode, containing new perceived images that are undefined in the mental episode.

Every valuable novel experience will be available for later retrieval. But rarely recalled experiences may become less and less accessible for subsequent retrieval. As Baddeley suggests, there exists a tendency for older memories to be recalled less frequently [11]. This kind of forgetting is realized by an activation level with exponential decay. Frequently recalled events are consolidated into the memory, which increases their probability for later recall (retrieval practice effect [11]). Retrieval is initiated by the formation of a retrieval cue. The emotional state, the salience and the activation level are the main determinants of successfully recalling an item. They are retrieved together with the stored event that matches it best for further steps in action selection. The matching algorithm can be influenced by context awareness and applied semantic rules that will be implemented in further work. If the retrieved event is part of an episode, the corresponding episode is further recalled to provide the prediction of possible future situations and their impact.

### *D. Action selection*

In this model not only the monitoring of actions but also the decision of selecting short and long-term actions are important. The main decisions for action patterns are made in the various control loops of the system, dealing with a number of proposed actions, which have to be scheduled due to their priority and feasibility. In general, there are three types of actions: competitive actions, cooperative actions, and combinations of the two. Due to their capabilities, we pre-define a group of motion primitives that represent the basic set of abstract tasks that a specific robot can execute. All behavior patterns are a composition of these motion primitives. In this example, we reduced the group to five simple actions: stop (remain on the present location), move (change location), carry (lift an object), and push (change location of an object without lifting). All actions need configuration data (object, direction), which will not be discussed here in detail. Furthermore, it is assumed that no more than three basic actions can be executed at the same time. A major concern in scheduling is how to combine the actions.

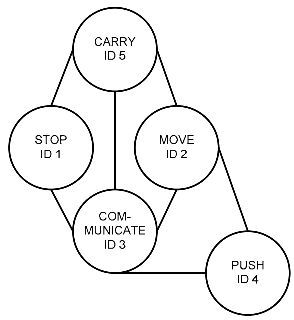


Fig. 3: Graphical representation of the basic actions

Fig. 3 depicts the general rules for making combinations, which is stored as a list that will be predefined due to the characteristics of the used mobile robot. All nodes, representing basic actions, which can be reached directly, can be executed in parallel: E.g. *communicate* (ID 3) can be executed with all other actions, while competitive actions like *move* (ID 2) and *stop* (ID 1) are not directly connected. Based on this concept, further rules for action selection can be defined:

- Combinations of actions are preferable to exclusive single actions.
- Currently executed action combinations have a higher priority than queued ones.
- Rearrangements of queued actions are conducted according to updating and priority labeling of control systems.
- Actions posses expire dates and can be restricted by control signals.
- Action patterns are also grouped and rated due to their emotional evaluation.

## IV. SIMULATION

To verify the behavior concepts sketched out in this article, a simulation environment has been defined. In this simulation, autonomous embodied agents (AEAs) have to roam their world, perceive information through their sensors, find and consume energy sources, and fight or cooperate with other AEAs.

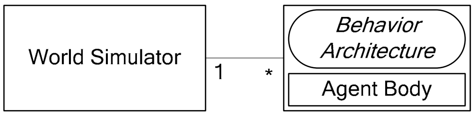


Fig. 4: Simulator Architecture

Fig. 4 shows the three basic modules of the simulation architecture:

- **World Simulator**: It contains the environment and basic knowledge about every agent. The tasks of this module are to collect action commands from the agents, verify them against the simulation rules, execute them, collect sensor data for each agent, and transmit this data back to the agent.
- **Agent Body**: This module works as an abstraction layer, decoupling the interface to the behavior architecture from the interface to the world simulator.
- **Behavior Architecture**: To enable the use of different types/realizations of behavior architectures, this module is put into a separate module for each agent. Currently, there exist two different types: one simple rule based architecture, and one implemented one using the behavior architecture described in this work.

This three-folded architecture enables an implementation of different types of agents with different behavior architectures in different worlds. Furthermore, the simulation can be distributed to several computers (e.g. calculate the world simulator on one computer and the agents on a second computer). The current application implemented in the world simulator is a competitive game in which two teams of agents have to find and collect energy. Each agent has its own autobiographic memory. The world contains, beside agents, obstacles and different types of energy sources, e.g. some of these energy sources cannot be opened by one agent alone. Each team has to compete with the other team. Within a team, "social" interactions are taking place, e.g. support in defense or cooperation in getting energy. The goal of this game is to survive as long as possible as a team.

To support the development of new behaviors for the AEAs, test-benches are used. These consist of a predefined set of sensor inputs which will evoke corresponding desires, emotions, or scenarios of interest.

## V. EVALUATION

The objective of this research is to develop a behavior architecture for action planning that should improve the pure reactive concept described in [12]:

- Calculate action plans to reach defined goals
- Solving conflicts of competing actions
- Cooperate within a team for better results of actions

To verify the results of the developed action planning model, two different types of test environments have been used. To determine solely the behavior architecture, a specific test-bench as shown in Fig. 5 has been developed. Within this test-bench, it is possible to instantiate one instance of the behavior architecture of an agent. This instance could be verified by simulating perceptual input that would normally originate from the world or the agent's body.

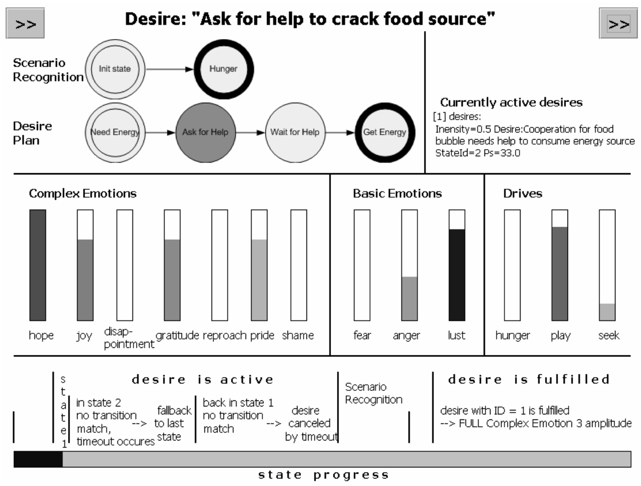


Fig. 5: Test-bench for decision unit

Internal values and the state of the agent have been visualized to show the impacts of different types of situations on the agent's drives, emotions and desires. The resulting actions were used as an output value to adapt the agents' set of mental images and episodes. With this method it has been possible to stimulate the agent's logic event base without the necessity of creating the exact surroundings to cope with the test scenario specifications. It has been shown in the simulation that at least one path of the action planning

model (reactive, routine or reflexive path) has returned an action within the selected test scenarios that represents situations with a high amount of perceived data as well as situations without any external stimuli. A conflict between those paths has been solved as described in III.D. Conflicts of actions within the high-level planning unit, e.g. caused by more than one active desire, have been solved by considering the intensity and probability of successful fulfillment of a desire.
The second test environment is a simulated area, in which instances of agents can be placed and where the cooperation between agents has been tested successfully.

## VI. Discussion and Conclusion

In this approach we have shown new concepts for autonomous behavior of mobile robots, improving the robot's capabilities of situation recognition, behavior arbitration and action planning, based on psychoanalytically founded principles. The simulation shows that this model, although not directly designed for robotic teams, allows potential task allocation and cooperation. With new memory system concepts learning capabilities have been imitated.

Due to the high level abstraction of the model and the universality of its methods, a broad range of areas of applicability for all types of mobile robots is feasible. Although the system is primarily designed for a total system, it is possible to extract functional modules. In order to estimate the importance of different methods, these functional blocks can be switched on and off separately in simulation. Thanks to the flexible simulation architecture, it is possible to use various types of environments showing significant problems and constraints due to the different application fields. This allows a fundamental and comprehensive evaluation of the capability and functionality of the embedded model. Although direct competing with other architectures has not been carried out so far, the simulation modules allow tests with other approaches.

In further steps, the introduced behavioral architecture, tested so far in simulation, will be used in robots in the real world in ongoing projects to show its benefits in practice and allow comparison with existing robot solutions.

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