MEXI: Machine with Emotionally eXtended Intelligence

- A Software Architecture for Behavior Based Handling of Emotions and Drives -

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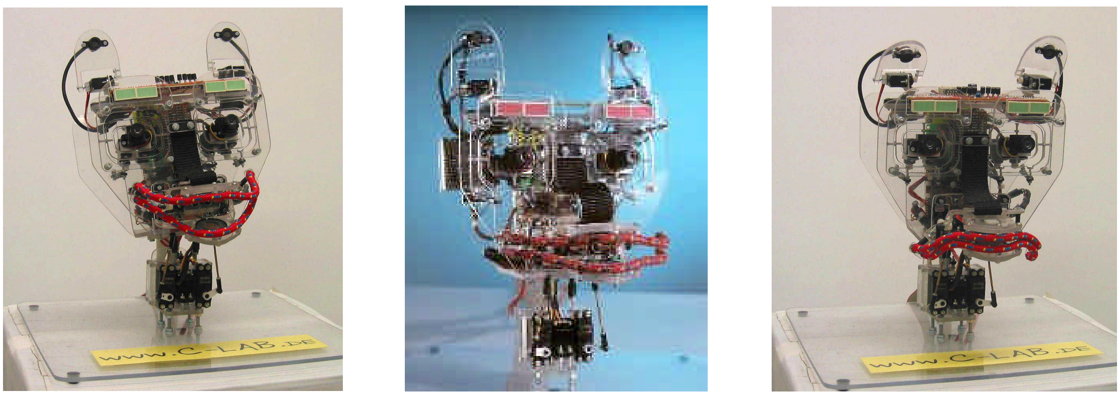
Abstract This paper describes the robot head MEXI which is able to show artificial emotions by its facial expressions and speech output. The focus of this paper is on MEXIs software architecture. MEXI does not rely on a world model to control and plan its actions like usual goal based agents. Instead MEXI uses its internal state consisting of emotions and drives to control its behavior. Furthermore we extended the behavior based programming paradigm originally developed by Arkin for robot navigation to support a multidimensional control architecture based on emotions and drives.

1. Introduction

During the last years the interest in "believable agents" has grown considerably as well in the software agent domain as in the robotics community. Often one of the major objectives for their design is the development of human like or human oriented interfaces in all domains where humans and robots or general IT-systems communicate. In Japan an entire design stream called Kansei Information Processing [10] deals with such issues as to make IP systems more acceptable for humans from a subjective point of view. This was also a major objective when building the robot head MEXI, our Machine with Emotionally eXtended Intelligence (see Figure 1). MEXI realizes an embodied interface that communicates to humans in a way that humans recognize as human or animal like.



a) joy b) neutral c) sadness

Figure 1: MEXI with different facial expressions

With its large ears and broad mouth MEXI should resemble a comic figure rather than an existing animal or even human being. This allows us to represent emotions more expressively in MEXIs facial expression. MEXI is equipped with two cameras and two microphones. MEXI has 15 degrees of freedom (DOF), that are controlled via model craft servo motors and pulse width modulated (PWM) signals. The neck has three DOF (pan, tilt, draw), eyes and ears each have 2 DOF and the mouth has 4 DOF. The eye brows are realized by a LED matrix that can be controlled in a block wise manner. Speakers in MEXIs mouth allow audio output. These facilities allow MEXI to represent a variety of emotions like joy, sadness, or anger. This often more resembles animals than humans due to MEXIs ears.

Our design goal was that MEXI should show attitudes in its communication behavior that humans would *interpret* as emotions or drives from their subjective point of view rather than exactly emulating them. For this purpose we developed a software architecture that uses emotions and drives to control MEXIs behavior rather than using explicit models of the environment and goals like in goal based agents [13] in order to control the behavior.

The remainder of this paper is structured as follows. Section 2 presents related work. Section 3 gives an overview of MEXIs software architecture, which is elaborated in Sections 4 and 5. While Section 4 concentrates on the purely reactive system, Section 5 explains how more complex behavior is realized via emotions and drives. Section 6 elaborates these principle concepts by an example. Section 7 gives an overview of MEXIs current realization. Finally Section 8 concludes the paper and gives an outlook on future work.

2. Related Work

In recent years there has been much work exploring the involvement of emotions in computing. This includes work on the use of emotions in human-computer interaction, Artificial Intelligence and agent architectures, which are inspired by the mechanisms of emotions, the use of emotions in computer-mediated communication and the study of human emotions through computers.

Numerous architectures have been proposed for artificial emotions. Some closely follow emotional theory, particularly in terms of how emotions are defined and generated. Arkin et al. [3] discuss how ethological and componential emotion models are incorporated into Sony's entertainment robots. The "homeostasis regulation rule" described in [1] is employed for action selection in Sony's *AIBO* and the humanoid robot *SDR* as well as in our approach MEXI. Canamero and Fredslund [8] describe an affective activation model that regulates emotions through stimulation levels.

Several expressive face robots have been implemented especially in Japan and USA, where the focus has been on mechanical engineering design, visual perception, and control. Examples are *Saya* [11] or *K-bot* [17] that are constructed to resemble young female face and are even equipped with synthetic skin, teeth and hair. Both can recognize several facial expressions and mimic them back to their spectator.

Carnegie Mellon University has developed a "talking head" called *Doc Beardsley* [18]. Similar to our work the Doc's emotion system, consists of drives and emotions. However, Doc Beardsley was designed to show a specific believable entertaining character. In contrast MEXI finally should adopt its reactions and communication behavior to the subjective preferences of its spectators.

Most similar to our work is the robotic head *Kismet* built at the MIT [6]. The organization and operation of Kismet's motivation system is strongly inspired by various theories of emotions and drives in humans and animals. Its target is to imitate the development and mechanisms of social interaction in humans. In contrast MEXI follows a constructive approach in order to realize the control of purely reactive behavior by its drives and emotions and to show this internal state by corresponding facial expressions and speech utterances.

3. Overview of MEXIs Software Architecture

MEXIs software architecture (see Figure 2) is designed according to Nilssons Triple-Tower Architecture, that distinguishes between perception, model and action tower [12].

The perception tower (*Perception*) processes the *sensor input*s from MEXIs cameras and microphones and abstracts them in two steps (feature analysis and object recognition, cf.

Section 4.1) into *objects* distinguished by MEXI. Such objects are e.g. human faces, the penguin Tux or MEXIs favorite toy (two colored balls). Furthermore these objects are weighted by a *strength* that informs about their importance (e.g. size of object or volume of a noise) in a standardized way for different sensors.

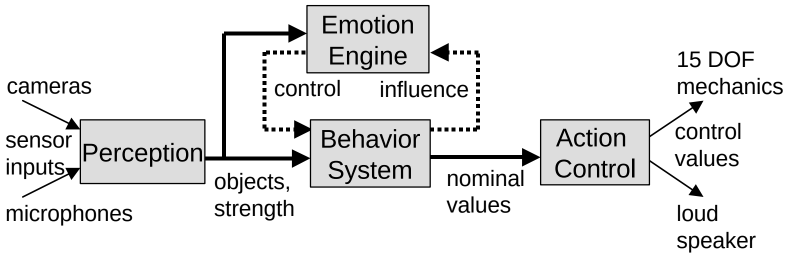


Figure 2: Software Architecture (Overview)

The model tower is realized by two components in our architecture, the *Behavior System* and the *Emotion Engine* that controls the Behavior System. The *Behavior System* processes the objects and their strengths delivered by the Perception in a purely reactive way without constructing any model of the environment like the subsumption architecture proposed by Brooks [7]. It is realized as a network of basic behaviors like smiling or tracking a human face using the principles of behavior based design and motor schemes described by Arkin [2]. The Behavior System determines which actions MEXI will perform by calculating a vector of nominal values for MEXIs actor system (mechanics and audio output). The *Emotion Engine* neither constructs any model of the environment but models MEXIs internal state as emotions and drives that control the purely reactive Behavior System. In turn the action selected by the Behavior System may for instance satisfy one of MEXIs drives and thus influence MEXIs internal state.

The action tower (*Action Control*) is responsible for processing the vector of *nominal values* for the different actors in such a way that among others MEXIs movements are performed in a smooth way or that visual and audio output are synchronized.

The entire software is realized in a dataflow oriented way and works in a periodical manner with sampling rates that are much higher than the changes of its internal parameters like emotions or drives. Hence a quasi continuous change of these system internal parameters can be assumed.

4. The Reactive System

The Perception, Behavior System and Action Control components realize a purely reactive system, that allows MEXI to directly react on the visual and natural speech inputs received from its environment by corresponding head movements, facial expressions and natural language ouput. In order to explain the principles of this behavior based reactive system we concentrate on the visual input and output in this paper. The handling of natural language is described in [4].

4.1. Perception

Currently MEXI perceives its environment with the aid of eyes (or cameras). MEXI can recognize human faces, the penguin Tux and its own special toy (two colored balls). MEXIs image analysis is based on a method, which was developed particularly for embedded reactive systems [15]. The image analysis is split up into two parts: the color segmentation algorithm for lower level feature detection and the template matching method for higher level object recognition.

The color segmentation algorithm finds regions with similar colors. These regions are approximated by moments of up to second order and represented by ellipses. The color segmentation works in two phases. In the first phase, region growing, the input pixels are processed and regions of height 1 are created. The second phase realizes region merging of the regions identified by the first phase [16].

Afterwards the position of skin regions or toys is calculated from the resulting regions. The positions of toys are directly communicated to the Behavior System. The position of skin regions is identified as a potential face location.

The located area is cut out off the entire picture and analyzed for faces with a template-based algorithm. A ratio template is composed of 16 regions and 23 relations. Each region is convolved with the grayscale image to give the average grayscale value for that region. Relations are comparisons between corresponding region values, for example, between the "left forehead" region and the "left temple" region. A relation is satisfied if the ratio of the first region to the second region exceeds a constant threshold. This method is described in detail in [14]. In addition in our approach relations are divided into four different groups according to their relevance and are weighted correspondingly. Based on the weighted relations the decision whether a face is detected or not is taken. The template is applied in various scales so that the faces can be recognized from different distances. If a face is identified with the scaled template the corresponding distance is communicated as the strength of the face perception to the Behavior System.

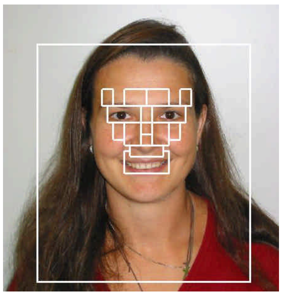


Figure 3: a) Face region b) Regions of ratio template

Figure 3a shows the result of the color segmentation algorithm. The skin region was detected (ellipse) and cut out as a larger area (rectangle). Within the area a face was found by template matching and is shown in Figure 3b.

4.2. Behavior System

MEXI is a highly interactive robot where fast reactions are essential for the working of the system. There is no cinematic model of the robotic head available and a model is also not desirable because MEXI is designed to be cheap and simple and therefore a fine calibration is not possible inhibiting the applicability of a cinematic model. Thus instead of using a complete cinematic model of the robot MEXI applies the paradigm of *Behavior Based Programming* developed by Arkin [2].

The main idea behind *Behavior Based Programming* is to model simple tasks individually and coordinate the outputs of these simple tasks by special *accumulators*. The inputs to the behaviors are the outputs of the perception, outputs from accumulators or other behaviors, building a behavior network.

The literature usually differentiates between two classes of coordination methods used by the accumulators [2, Chapter: Behavior-Based Architectures]:

- *Cooperative Coordination*: The outputs of *all* behaviors are merged (e.g. by a weighted sum or by vector summation)
- *Competitive Coordination*: The output of *one* behavior is chosen resulting in a winner-takes-all strategy (e.g. by using priorities)

To realize smooth motions (e.g. robot navigation tasks) cooperative strategies are preferred because cooperative accumulators seldomly have leaps in the outputs. A famous example are Arkin's *Motor Schemes* where each behavior generates a 2D motion vector. Motion vectors of different behaviors are mixed simply by vector summation and normalization.

In some areas an exclusive selection mechanism is desirable, e.g. when applying a concrete rule like “`Look to position x,y`”. In such cases competitive accumulators should be used. The Subsumption Architecture developed by Brooks [7] is a good example of such a competitive architecture. It uses priority-based arbitration via inhibition and suppression.

Because MEXI has to fulfill both smooth continuous actions (e.g. movement of the head) and exclusive actions (e.g. line of sight of the eyes) a combination of a cooperative and competitive voting mechanism combined with external gain values has been developed for the coordination of MEXIs servo motors. Actually MEXIs behavior network only consists of one set of behaviors and one accumulator (see Section 5, Figure 5).

Each of these motor-behaviors b generates a fixed-sized vector $\vec{C}_b$ containing 15 triplets (one for each servo motor s) consisting of the nominal value $c_{s,b}$, a vote $v_{s,b}$ for each of the nominal values and a mode flag $m_{s,b}$ (cooperative vs. competitive):

$$\vec{C}_b = \begin{pmatrix} (c_{1,b}, v_{1,b}, m_{1,b}) \\ (c_{2,b}, v_{2,b}, m_{2,b}) \\ \vdots \\ (c_{15,b}, v_{15,b}, m_{15,b}) \end{pmatrix}$$

The votes are used to model different levels of importance and are computed internally by each behavior. They are often directly influenced by the strength of the input perception. Using the vote values a behavior can signal whether the output is of high importance ($v_{s,b}=1$) or should have no influence at all ($v_{s,b}=0$).

To compute the nominal values for the servo motors an accumulator S was developed. The input to S are the output vectors $\vec{C}_b$ of the motor behaviors. A gain value g_b is attached to each of the input vectors. These gain values are used to *configure* the behavior network by higher control levels like the Emotion Engine as explained in the next section. The output of S is a vector $\vec{R}$ containing the nominal values r_s for the servo motors and a vector $\vec{I}$ representing the influence of the behaviors on the output.

The idea behind the motor accumulator S is to calculate the nominal value for each servo motor individually depending on a ranking of the behaviors’ outputs. The nominal value is either computed as a weighted median of all cooperative nominal values if the highest ranked behavior is cooperative or as the direct output of the highest ranked competitive behavior.

In detail the motor accumulator S works as follows (B is the number of motor behaviors and S is the number of servo motors):

- For each servo motor s the output r_s is evaluated individually.
  - For each motor-behavior b a weight $w_{s,b} = g_b \cdot v_{s,b}$ is computed as a product of *gain* and *vote* to represent both external and internal parameters. The weight is needed to do the ranking of the behaviors.
  - If the behavior b with highest weight is competitive, a winner-takes-all strategy is used and the resulting nominal value for servo s is $r_s = c_{s,b}$
  - Else a weighted median of all cooperative values is evaluated:

$$r_s = \frac{1}{W_s} \sum_{\substack{b=1 \\ m_{s,b}=coop.}}^{B} w_{s,b} \cdot c_{s,b} \text{ with } W_s = \sum_{\substack{b=1 \\ m_{s,b}=coop.}}^{B} w_{s,b}$$

- For each behavior b an influence value I_b is calculated describing the overall influence of the behavior on the vector of nominal values $\vec{R}$ ($i_{s,b}$ is the influence of behavior b on the nominal value for servo s and I_b is the median influence over all servo motors):

$$I_b = \frac{1}{S}\sum_{s=1}^{S} i_{s,b} \quad \text{with } i_{s,b} = \begin{cases} 1 & \text{if } b \text{ is competitive and } w_{s,b} \text{ is highest weight} \\ 0 & \text{if } b \text{ is competitive and } w_{s,b} \text{ is not highest weight} \\ \dfrac{w_{s,b}}{W_s} & \text{if } b \text{ is cooperative} \end{cases}$$

The vector of nominal values $\vec{R}$ is handed over to the Action Control. The influence vector $\vec{I}$ is needed for higher control levels for the evaluation of the behavior of the reactive system as explained in the next section.

4.3. Action Control

MEXI uses model craft servo motors to realize head movements and facial expressions. Characteristic for these devices is that they try to reach the nominal value in very short times. This would result in abrupt movements that are not desirable for the representation of emotions. Therefore we realized an API for the Action Control component that allows the Behavior System to specify a movement velocity besides the nominal value for each servo motor. For clarity reasons this was disregarded in Section 4.2. The Action Control then calculates for each nominal value a series of intermediate points in order to reach the nominal value with the desired velocity. Then according PWM signals for the corresponding servo motors are generated in real time. Since the Action Control is realized on a 16-bit C167 microcontroller, this is supported by specific periphery. Furthermore the Action Control prohibits movements that could destroy MEXIs mechanics.

5. The Emotion Engine

Unlike many goal directed agents [13] MEXI has no internal model of its environment to plan and control its behavior but uses its emotions and drives for that purpose. In principle MEXI has two objectives that control its actions. One is to feel positive emotions and to avoid negative ones. The second objective is to keep its drives at a comfortable (homeostatic) level. The Emotion Engine is responsible for maintaining MEXIs internal state representing the current strength of emotions and drives. This internal state is used in a feedback loop to configure the Behavior System in such a way that appropriate behaviors are selected in order to meet the two objectives stated above. The Behavior System informs the Emotion Engine how large the influence of each behavior was for the actions actually performed by MEXI. This information is evaluated by the Emotion Engine and in turn together with external perceptions influences the internal state of MEXI, i. e. its emotions and drives. This feedback loop is described more closely in Section 5.2 after a more detailed description of the emotions and drives is given in Sections 5.1.

5.1. Emotions and Drives

Besides the control of MEXIs behavior the emotions should also attract human attention. For MEXI we distinguish a small set of basic emotions that can be represented easily by MEXIs facial expression and audio output, i.e. anger, joy, sadness and disgust. Joy is a positive emotion, which MEXI strives for, while the others are negative ones that MEXI tries to avoid. According to psychologists these emotions can also be recognized easily by humans in facial expressions [9].

In order to realize a simple control mechanism for MEXI we consider mainly *homeostatic drives,* although in humans a variety of additional drives (cyclical drives, default drives, exploratory drives, noxious drives, anticipatory drives) can be observed [5]. Homeostatic drives motivate behavior in order to reach a certain level of homeostasis. Examples in humans are hunger or thirst. MEXI has for instance a communication drive or a playing drive. Violation of the homeostasis is the more likely to cause according behavior the more the discrepancy between homeostasis and the actual "value" increases. Furthermore an *exploratory drive* lets MEXI look around for new impressions if none of the homeostatic drives causes any behavior. In MEXIs Emotion Engine each emotion e is represented by a strength value str_e between 0 and 1 and each drive by a strength value str_d ranging from -1 to 1. The principle development of emotions and drives over time is shown in Figure 4.

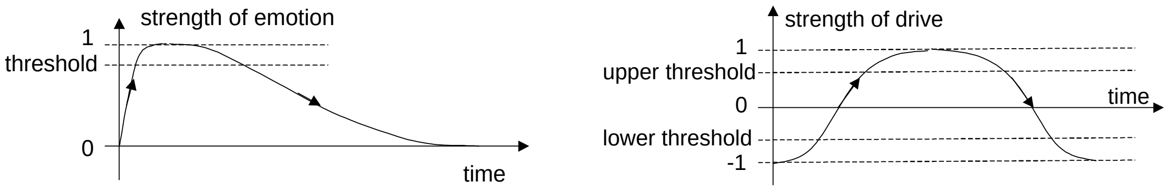


Figure 4: a) Representation of MEXIs emotions b) Representation of MEXIs drives

For each emotion a threshold defines when MEXIs behavior will be configured to show this emotion, e. g. by corresponding facial expressions. The increase of an emotion in MEXI is caused by perceptions of its environment and by the drives (their fulfillment or oversatisfaction, resp.). The decrease happens automatically with a certain amount per time unit. For this purpose a time triggered excitation function is associated with each emotion. Furthermore we maintain a network of interdependencies between MEXIs emotions [4] since some emotions inhibit or enforce others.

For the drives 0 represents the level of homeostasis, 1 represents a very large drive striving for its satisfaction and -1 expresses that the drive was overly satisfied. In contrast to emotions each drive has an upper and lower threshold that define when the drive will dominate MEXIs behavior. In order to realize proactive behavior the increase of MEXIs drives happens automatically with a certain amount per time. This is realized by a time triggered excitation (see Figure 5). To avoid that MEXIs behavior oscillates in order to satisfy competing drives a certain threshold has to be reached before a drive will dominate the behavior. Drives can be satisfied (their strength decreases a certain amount per time unit) if MEXI executes corresponding behaviors. MEXIs communication drive for instance is satisfied when MEXI sees a human face and follows it by corresponding head and eye movements (see Section 6).

5.2. Control of the Behavior System by the Emotion Engine

As already mentioned the feedback loop between the Emotion Engine and the Behavior System realizes two principle objectives a) feel positive emotions (joy), and avoid negative ones (anger, sadness, disgust) and b) keep drives in homeostasis. This feedback loop is depicted in Figure 5 that describes MEXIs software architecture in more detail. For clarity reasons only some behaviors, drives and emotions are shown.

The *Excitation* components allow to realize proactive behavior. Each drive and emotion has a time triggered function for excitation. For MEXI we realized a positive excitation for the homeostatic drives since their strength increases automatically and a negative excitation for emotions to realize automatic decay. Also oscillating excitement functions could be used if for instance cyclical drives should be realized.

The *Configuration* component determines from the actual percepts and the internal state of emotions and drives which behaviors of the Behavior System should be preferred by setting the gain values g_b for each behavior *b*. If a drive reaches its upper threshold the gain for the behaviors, that will satisfy that drive, is increased by a certain (variable) amount per time. If a drive reaches its lower threshold the gains for the "satisfying" behaviors are decreased respectively. If a percept causes a certain emotion in MEXI the emotion strength is increased. If a certain threshold is reached the gains for according behaviors e. g. those that generate the corresponding facial expression are set to 1. Conflicts between drives are resolved in MEXI by a fixed priority.

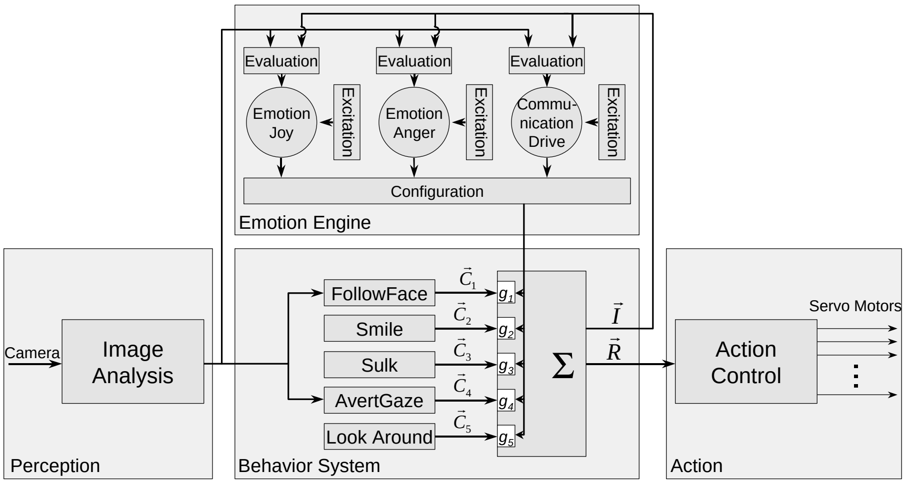


Figure 5: Software Architecture (Detail)

The *Evaluation* component evaluates the influence vector *I* calculated by the accumulator Σ in the Behavior System in order to determine whether the preferred behavior really dominates the actual actions activated by Action Control. This decision is positive, if for competitive behaviors the influence equals 1 and for cooperative behaviors a specific threshold is exceeded. If the behavior was initiated by an emotion the negative excitation function is switched on for subsequent cycles in order to let the emotion strength decrease automatically. In case of drives the strength of the drive is decreased by a specific amount. This is repeated if the behaviors are preferred also for subsequent cycles until the lower threshold of the drive is reached.

The Excitation, Configuration and Evaluation components are realized like the Behavior System using the behavior based programming paradigm. The outputs of the accumulators are in this case decay or rising rates for the excitation functions, gain values for configuration of the Behavior System and strength values for emotions and drives resulting from the evaluation of current percepts and influences (influence vector *I*) of behaviors.

6. Example Session

For an example session have a look at the diagrams in Figure 6. At the beginning of this session no human face is visible for MEXIs cameras. The strength of the face perception is zero and the votes of the *FollowFace* behavior are also zero because the votes of *FollowFace* are the identity of the strength of the face perception.

There is a behavior *LookAround* corresponding to MEXIs exploratory drive with constant vote 0.5 and constant gain 1.0 which lets MEXIs eyes and head move around to find interesting things (e.g. human faces). One can think of this behavior as a default behavior because it does not depend on the perception and has influence as long as no interesting things are visible (other competitive behaviors like *FollowFace* with higher weights may suppress the output of *LookAround*).

Starting at time t_0 a person walks towards MEXI. The vote of the *FollowFace* behavior raises until the persons stands right in front of MEXI at time t_3.

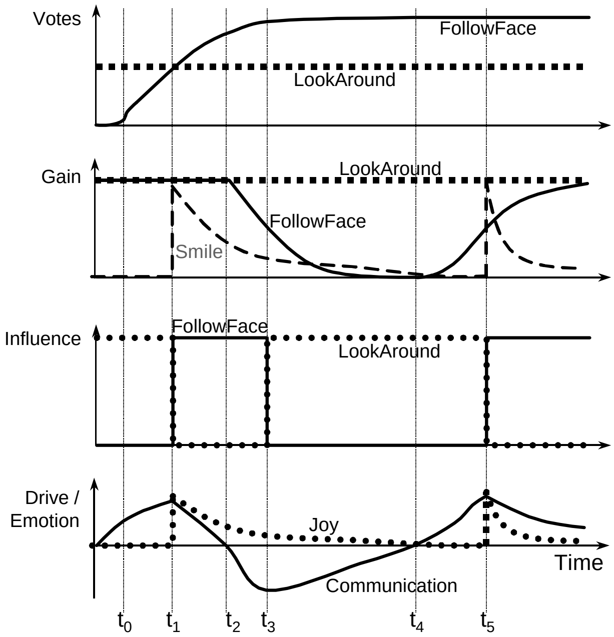


Figure 6: Example Session

At time t_1 the weight (see Section 4.2) of *FollowFace* is higher than the weight of *LookAround*. *FollowFace* is competitive and therefore it's influence goes to one resulting in a decrease of the *Communication Drive*. At t_2 the *Communication Drive* becomes negative (lower threshold = 0) and therefore the gain value of *FollowFace* starts going down. At time t_3 the weight of *LookAround* is the heighest again so that MEXI starts looking around again. Over the time the *Communication Drive* increases until it is positive again (t_4) (upper threshold = 0) and the *FollowFace* gain value raises. At time t_5 the weight of *FollowFace* is higher than the weight of *LookAround* so MEXI starts looking at people again.
The emotion *Joy* is set to one each time the influence of *FollowFace* raises, i.e. the communication drive starts being satisfied. As a result of the raising of the emotion *Joy* (threshold = 1) the gain value of the behavior *Smile* also raises to one and MEXI starts smiling.

7. Implementation

MEXIs three towers (Perception, Model, Action) are realized on three different platforms. The computer vision algorithms are implemented on a 100 MHz Philips TriMedia 1100 processor analyzing the analog camera signal of one of MEXIs eye cameras with the full framerate of 25 frames per second. The datastructures of the regions of interest are transmitted via a serial link to a PC running Linux. On this PC the behavior system and the emotion engine are executed. The Behavior System and the Emotion Engine are triggered by the perception and therefore are evaluated with a framerate of 25 Hz as well. Both Behavior System and Emotion Engine are implemented using the Java language. Finally the Action Control is implemented on a C167 16-bit microcontroller which is capable of generating the 15 PWM (pulse width modulated) signals which are needed for MEXIs 15 servo motors. The communication between the PC and the microcontroller is realized using a serial link.

8. Conclusion

In this paper we presented the robot head MEXI with specific focus on its software architecture. The software architecture follows the triple tower architecture presented for goal based agents. However no explicit world model and goal representation is used to plan MEXIs actions. Instead we realized a feedback loop for control relying on artificial emotions and drives in MEXIs Emotion Engine. The underlying Behavior System and the Emotion Engine are based on the behavior based programming paradigm extending Arkins motor schemes to a multidemensional model of reactive control. Up to now the work on MEXI concentrated on the synthesis of emotions and drives, using a constructive approach rather than emulating human ways of "feeling". Our experiences with MEXI on different public exhibitions and fairs show that MEXI although realizing only a restricted set of emotions an drives attracts human spectators and maintains their communication interest. Future work will be directed towards the recognition of emotions from facial expressions and speech input, in order to react more dedicatedly to the mood of human counterparts.

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