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Robot regulatory behaviour based on fundamental homeostatic and allostatic principles

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Abstract

Animals in their ecological context behave not only in response to external events, such as opportunities and threats but also according to their internal needs. As a result, the survival of the organism is achieved through regulatory behaviour. Although homeostatic and allostatic principles play an important role in such behaviour, how an animal's brain implements these principles is not fully understood yet. In this paper, we propose a new model of regulatory behaviour inspired by the functioning of the medial Reticular Formation (mRF). This structure is spread throughout the brainstem and has shown generalized Central Nervous System (CNS) arousal control and fundamental action-selection properties. We propose that a model based on the mRF allows the flexibility needed to be implemented in diverse domains, while it would allow integration of other components such as place cells to enrich the agent's performance. Such a model will be implemented in a mobile robot that will navigate replicating the behaviour of the sand-diving lizard, a benchmark for regulatory behaviour.

Keywords: Allostasis; Homeostasis; Regulatory Behaviour; Action Selection; Reticular Formation; Cognitive Architecture.

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1. Introduction

The natural behaviour of animals reflects how these organisms fully adapt to their different and unique environments. Their complex behavioural repertoires not only are the result of learning and evolution; they also are dependent on the animal's internal needs and the occurrence of events in their ecological context. Thus, animal behaviour goes beyond reflexive responses toward opportunities and threats that the environment provides [1].

Different internal needs i.e. thirst or hunger, drive animals to perform different regulatory behaviours, i.e. drink or eat. A very enlightening example can be provided by analysing the behaviour of the Namib desert Lizard [2]. In the Namib desert, temperatures change very rapidly and reach a maximum of around 45-50ºC. However, the desert lizard can regulate its body heat by diving beneath the sand towards cooler areas. When surface temperature is around 30ºC, the sand-diving lizard emerges from the sand to increment its body heat by pressing its ventral surface against the substrate. Once body heat is restored, and the surface temperature starts to increase, the lizard stretches its limbs, lifting its body from the hot sand. Similarly, when the temperature rises above 40ºC, the lizard dives again approximately seven centimeters beneath the sand, to spend there the warmer period of the day.

The adaptative behaviours that the sand-diving lizard exhibits in response to the changing temperatures of the Namib desert are the perfect example of regulatory behaviour based on homeostatic principles. Homeostasis accounts for those independent mechanisms that ensure fulfilment of specific needs (i.e. hunger through levels of ghrelin in the arcuate nucleus of the hypothalamus [3]). In terms of homeostasis, the lizard has a desired temperature value around the 30ºC that needs to be maintained. Other temperatures create a motivational tendency that drives the lizard to perform a regulatory behaviour that brings the actual body temperature back to balance.

Although the homeostatic balance of body temperature seems to be easily maintained in the case of the sand lizard, temperature regulation is not the only concern of the animal. Several homeostatic systems operate in parallel in order to efficiently control other internal needs such as thirst, hunger, security or resting. Allostasis accounts for the coordinated fulfilment of these different homeostatic systems, following principles of priority and urgency, to ensure the survival of the organism. Thus, animals could prioritize security over thirst by staying at burrow when a predator is in the surroundings. However, if thirst levels are extremely unbalanced, the urgency for drinking could promote exploratory behaviour in search of water even if it implies the risk of predation [4].

Simplified computational models for homeostatic and allostatic control can be seen in figure 1 and 2 to facilitate the understanding of the main insights. These models are inspired by previous works [5, 6] supporting homeostatic and allostatic control of behaviour as emotional expression. Figure 1 depicts the key components of an unspecified homeostatic system. Computationally, maximum and minimum limits are normalized, so actual values (the current state of a homeostatic system at a given time) vary from 0 to 1. The system is identified as balanced while the actual value (aV) remains between the homeostatic limits defined by the desired value (dV) range. The desired range can also vary between different homeostatic systems. Only when the aV is set outside the dV range, a motivational tendency drives the animal to bring the actual value back to balance by behaving consequently. The intensity of this tendency is known as urgency and accounts for the distance between the aV and the dV, when aV is outside its range.

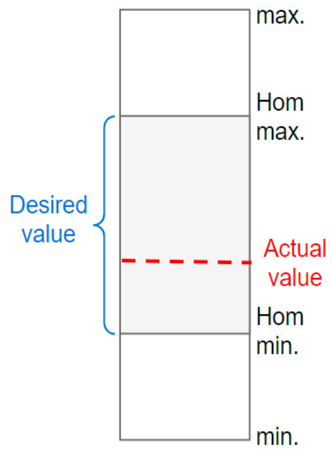

Fig. 1: Homeostatic mechanism. Needs drive the animal to restore the unbalance between actual and desired values. Image reproduced from [5].

Figure 2 represents how actions are selected based on allostatic principles. For simplicity, only three homeostatic systems have been considered (security, warmth and thirst), arranged from left to right according to their priority. The aforementioned trade-off problem between thirst and security is analysed by altering thirst's aV. In the first case (pointed out in Fig. 2 with the clear blue dashed line representing thirst aV), where security and thirst drives compete against each other, the resulting selected action prioritizes security, not only because its urgency is higher but also because security has a higher priority level. Thus, the animal hides from possible predators despite its slight need for water. However, in the second example (dark blue dashed line), the aV of thirst is so unbalanced that endangers the survival of the animal. Here, because the thirst homeostatic system is highly unbalanced, the motivational tendency for water acquisition stands out above the need for security due to its urgency. And so, action selection prioritizes the satiation of thirst. This example illustrates the situation where, even in the presence of predators, preys risk their lives for a sip of water.

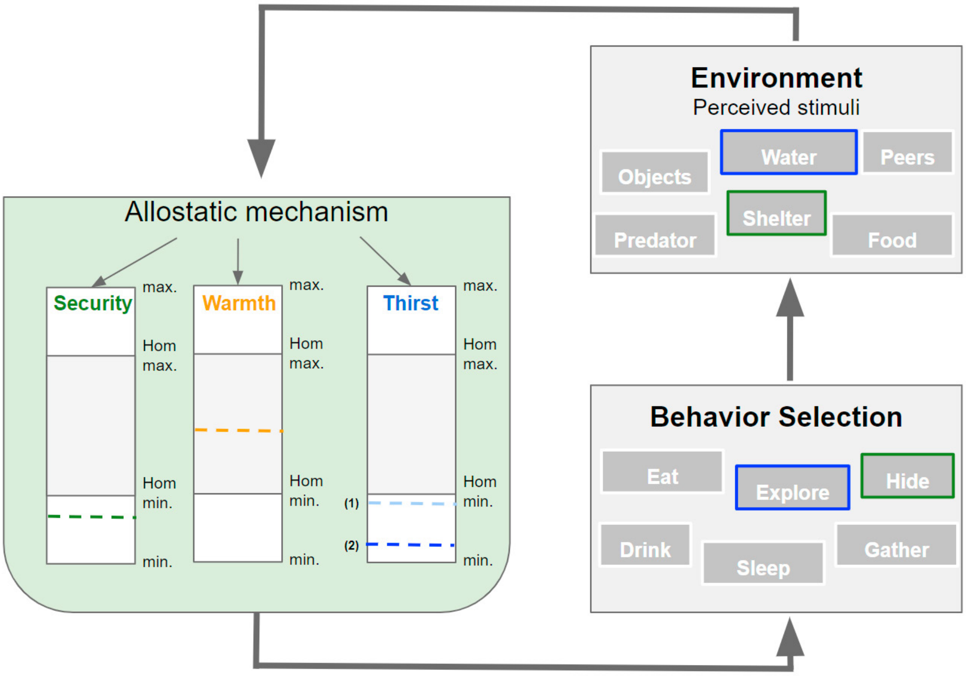

Fig. 2. Allostatic controller. The organism selects the action that better ensures survival by means of priority and urgency principles. Clear and dark blue dashed lines in thirst homeostatic system represent different aVs, and so promoting regulatory behaviour based on different homeostatic systems. Case 1 promotes hiding behaviour fulfilling security need, while case 2 promotes exploration for water to fulfil thirst need. Image reproduced from [6].

Although natural behaviour seems to be well explained by the coordinated interaction of the different homeostatic systems, and thus dominated by the strongest motivational tendency, how these tendencies are calibrated is not well understood yet. The weighting of different homeostatic systems providing them with different levels of priority is a concept that partially matches with Maslow's hierarchy of needs [7]. Two main ideas can be extrapolated to allostatic regulatory behaviour from Maslow's pyramid. First, Maslow proposed that the fundamental motivational systems are multiple and independent. This idea perfectly matches with the existence of different homeostatic systems determined by different dynamics, stimuli, neural substrates and neurotransmitters. Secondly, Maslow also claimed that these drives are arranged according to their priority, forming a hierarchy, where higher needs would only be considered if those constituting the base of the pyramid are fulfilled.

However, contemporary authors point out the necessity of reviewing and updating Maslow's motivation theory [8]. Specifically, the hierarchy of needs faces three main constraints. First, it is a theory specifically developed to explain only human behaviour and not behaviours of other animals. Second, the needs of the same level do not differ in priority, so all physiological needs such as warmth, thirst, hunger or resting are considered equally important. And third, Maslow considered that motivation's dynamics are intrinsic to the self. However, internal needs should also be calibrated according to specific threats and opportunities that the immediate ecological context provides to the organism.

The present paper describes the first steps towards developing a model of allostatic regulatory behaviour. This model will consider scientific evidence on the field of psychology and neuroscience, integrating main properties of Maslow's hierarchy and recent research on Brainstem's Reticular Formation. Specifically, Reticular Formation serves as the main inspiration for the design of this upcoming model. Its role in controlling generalized CNS arousal and action selection provides us with the more fundamental principles of regulatory behaviour and, at the same time, its implication supports the appearance of rich behavioural repertoires.

After presenting preliminary data, a benchmark based on the sand-diving lizard behaviour is outlined. This benchmark will not only allow us to assess the regulatory behaviour of a synthetic agent endowed with our model, but it also will contribute to replicate previous works on allostatic control.

2. Previous work on allostatic control

A relevant contribution to the topic has been provided in 2010 by Fibla, Bernardet and Verschure [9]. In this work, allostatic control is implemented in a mobile robot by using a model of hippocampal place cells. Here, different homeostatic systems are represented as gradients (or vector fields) and the desired values as locations in such space. Thus, the robot navigates in the environment, depending on whether this action brings the actual homeostatic value closer to the desired one in each gradient. Influence of each gradient is weighted differentially.

The integration of allostatic and homeostatic principles to the place-cell-based navigation of the robot not only achieves regulatory behaviour reflected on its trajectory but also take advantages from path planning towards desired stimuli. However, this allostatic system has also some limitations to be considered. On the one hand, the allostatic control system is specifically designed for navigation, making difficult its generalization to other domains such as emotion regulation. On the other hand, the evidence seems to suggest that the basis of behaviour regulation should be computed at the brainstem level and not in forebrain areas such as the hippocampus.

Nevertheless, this work still represents a state-of-the-art benchmark for robotic regulatory behaviour. Thus, replication of this study, together with the overcoming of its limitations, support the design and implementation of a new model of regulatory behaviour based on allostatic and homeostatic principles.

3. Neural substrates for homeostasis and allostasis

In this section, since emotions (i.e. fear) use to be the predecessor of regulatory behaviour (i.e. scape), we first review recent neuroscientific evidence that highlights the relevance of the brainstem in emotional regulation. We then proceed to discuss a way in which this evidence can be applied to the implementation of an allostatic control model, as well as the advantages it provides.

3.1. Generalized CNS arousal is key for cognition.

Generalized CNS arousal is proposed as one of the most primordial capacities of the brain since a neural substrate devoted to this purpose would be responsible for waking up the rest of the areas in the brain. According to research [10], the best neural substrate candidate to be endowed with this capacity is the Reticular Formation.

The medullar Reticular Formation plays an essential role as an intrinsic (integrating homeostatic information) and extrinsic (driven by sensory input) generator of activity. Moreover, "giant neurons" within the reticular activating systems contribute to both ascending and descending arousal pathways. Additionally, interneurons within the Reticular Formation can modulate the giant neuron's activation by exerting inhibition (Fig.3).

This work also proposes that the CNS plays a key role in the regulation of emotional expression. In this view, the emotional expression could be computed as a vector, where different feelings account for different angles of the vector, and the length of it is assigned by the generalized CNS arousal of the organism.

3.2. The role of the medial Reticular Formation in action selection.

Traditionally, action selection has been considered deeply related to basal ganglia [11]. However, Humphries, Gurney and Prescott [12] suggest that, although this area would still be contributing to motor control, basal ganglia do not represent the most fundamental action-selection system. Instead, they propose the medial Reticular Formation (mRF) as a mode selector of the global behavioural state. In earlier work [13], they modelled the brainstem Reticular Formation in a way consistent with what has been proposed in [10]. In their model, giant neurons (referred to as projection neurons) are exciting neurons outside of the Reticular Formation, while interneurons would be inhibiting these projection neurons. Moreover, both projection neurons and interneurons are grouped into stacked clusters, and the radial dendritic fields of the former allow sampling of ascending and descending input from both other clusters and sensory systems (Fig. 3).

But importantly, the configuration of the Reticular Formation system is thought as the bottleneck "*needed in order to convert the massively parallel and distributed information capacity of the cerebral hemispheres into a limited-capacity, sequential mode of operation presented in action selection for coherent behaviour*" [14].

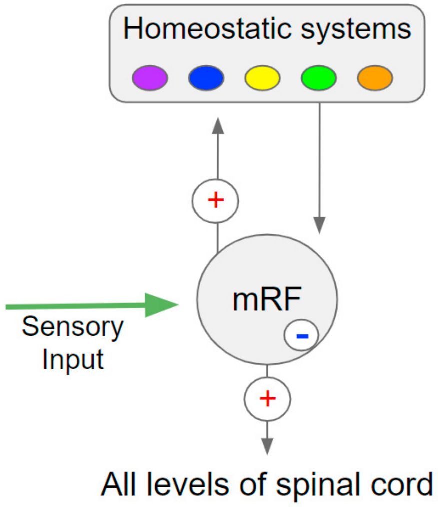

Fig. 3. Computational model of the medial Reticular Formation. Projection neurons excite ascending and descending arousal pathways. Interneurons inhibit projection neurons within the mRF. Unprocessed sensory input arrives directly to the mRF as well as information from the different homeostatic systems.

4. Behavioural repertory

So far, the mRF has been proposed to play an essential role in controlling generalized CNS arousal and action-selection. However, the action selected can vary in response to the same motivational tendency within a very similar context. For instance, mice vary their defensive behaviour based on contextual characteristics such as promoting flight or avoidance of predators when it is possible and freezing when it is not. But additionally, when the predator comes closer and closer, muscle tension increases and mice exhibit an abrupt change in behaviour by attacking and biting the predator's head, independently of flight opportunities [15].

This abrupt change in mice behaviour can be explained by Merker's selection triangle [11]. Merker suggests that action selection is not only based on internal needs but also the disposition of targets. Thus, three steps should be taken to select the more appropriate action. First, and in concordance to Maslow's ideas, the organism follows a motivational ranking. Second, the proper target needs to be selected. Third, the most appropriate action is selected.
In this view, by having a mechanism able to compute emotional expression as a vector, the behavioural repertory can be arranged by the length of the vector as a response to different levels of arousal. Thus, different behaviours (Fig. 4) can be expressed depending on the level of arousal needed to trigger it. For instance, if a predator is presented to a rodent, the level of arousal could depend on the distance between them. Thus, the animal can exhibit a complex behavioural repertory, from defensive behaviour such as hiding, scaping and freezing to aggressive behaviour such as biting.

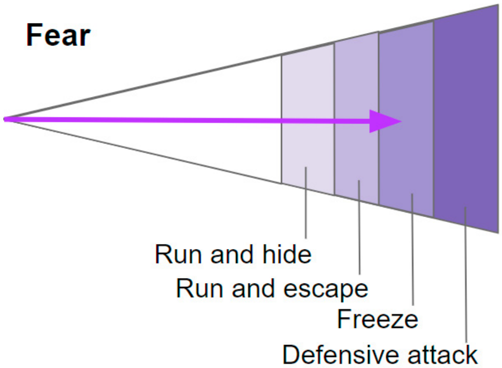

Fig. 4. Behavioural repertory for fear motivational tendency. Regulatory be-haviour as a result of the length of the vector (arousal level). Changes in colours illustrate the threshold between different actions.

5. Methods

Our model, currently under development, aims to follow design guidelines based on the aforementioned neuroscientific evidence. Each version of this model is being implemented in a synthetic agent (robot) allowing regulatory behaviour. As the model increase in complexity and integration of different brain structures are done, the tasks designed to assess robot regulatory behaviour also increase in complexity.

Current implementation models regulatory behaviour based on homeostatic principles. Two homeostatic systems, simulating hunger and thirst, drives the robot to perform approach behaviour towards its related stimuli (food or water) only when unbalance, namely when the actual value is outside the limits of the desired value range. The desired value range is set equally for both homeostatic systems, having a maximum of 0.7 and a minimum of 0.30. Additionally, the approach behaviour consists of forwarding movements oriented to the stimuli (fiducials) representing the resources (Fig.5). When the robot was close enough to the stimulus, approach behaviour stops, and the associated need is fulfilled.

Results for this regulatory behaviour based on homeostatic principles are provided in the next section. As predicted, action selection does not take advantages from coordination between different homeostatic systems, since principles of priority and urgency are not considered yet. Future work section describes how allostatic control will be achieved based on state-of-the-art research and how future evidence can be considered.

6. Results

In this section, we present the preliminary results of the current version of the model. The model is implemented into a real mobile robot that can exhibit several behaviours in the form of different navigational profiles. Visual stimuli detection is achieved by using a JeVois camera, which already incorporates computer vision modules for feature extraction, allowing for fiducial identification. Approach behaviour to targets is achieved by modulating motion based on fiducial location.

6.1. Homeostatic control.

Homeostatic control was first tested by modelling one single homeostatic system: thirst. This system has, as specified in the introduction, normalized values. A decay factor dependent on time modules the actual value (aV). Only when the aV is outside the dV range (0.70 – 0.30), the agent exhibits the regulatory behaviour associated with this need. To do so, fiducials are presented in front of the robot representing water or food, so the robot can autonomously perform an approach behaviour based on its internal needs (Fig. 5). If such approach behaviour is performed towards the correct target (water), the aV of the homeostatic thirst system is updated by increasing its aV until its maximum homeostatic limit.

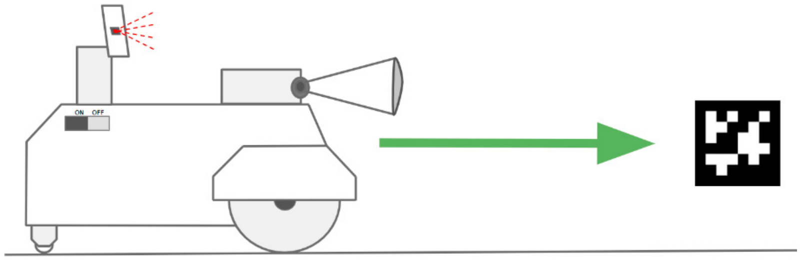

Fig. 5. Experimental set up for testing homeostatic control. Different fiducials are presented to the robot. Only when homeostatic systems are unbalanced, they trigger approach behaviour to the corresponding stimuli.

A second experiment was performed by adding a new homeostatic system to regulate hunger. The hunger homeostatic system has the same specificities than the previous one, except that the decay factor is set to a lower value, simulating a realistic thirst-hunger trade-off situation. Dynamics of both homeostatic systems can be observed in Fig.6. In this plot, five main events can be identified. First, the fulfilment of both needs through approach behaviour only occurs when aV is below the minimum limit of the dV. Second, the thirst aV decays twice as fast as the hunger aV due to the different decay factors of the homeostatic systems. Third, while aV is below dV, the robot immediately executes an approach behaviour as soon as its related stimuli are presented. Lower aVs account for the no presentation of the related stimuli. Fourth, approach behaviours set aV equal to the maximum of the dV range. Fifth, both thirst and hunger homeostatic systems work independently, and no mechanism coordinates their needs based on priority or urgency principles.

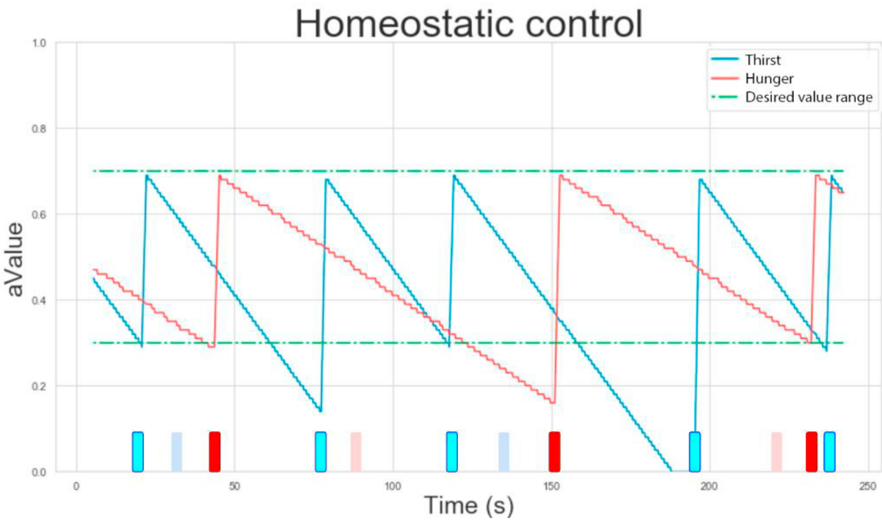

Fig. 6. Homeostatic control. Data recorded during a session where the robot is presented to different fiducials representing food and water. Bars in the x-axis depict the presentation of water (blue) or food (red) stimuli. Intense bar colours represent when stimuli presentation is followed by approach behaviour. However, approach behaviour towards a given stimulus was only performed when its related system was unbalanced, so if stimuli were presented while aV remains among dV limits, presentation of stimuli do not trigger any response as faded bars represent.

7. Future work

7.1. Allostatic control.

Next steps following this work will focus on the coordination of different motivational tendencies through allostatic control. As mentioned above, our model aims to convert homeostatic information into a vector. The angle of the vector will be computed by integrating information from the different homeostatic systems, whereas its length will be given by the magnitude of the motivational tendency. This magnitude is computed by the distance to the closer homeostatic limit when aV is outside the dV range. This variable magnitude represents the intrinsic source of arousal.

Selected regulatory behaviour is the result of the comparison between these vectors following two principles. (a) Priority: Homeostatic systems are arranged following prioritization criteria inspired by Maslow's hierarchy of needs. (b) Urgency: Operationalized as the distance between aV and dV. The higher the distance, the higher the magnitude of its associated motivational tendency. The following equation describes our proposed arbitration between vectors based on the urgency and priority principles. Selected regulatory behaviour is based on need i while:

$$N_i(aV_i - mindV_i) - Rd_i > N_j(aV_j - mindV_j) - Rd_j$$

$N_i(aV_i - mindV_i)$ accounts for the magnitude of the motivational tendency (Need) i computing distance between aV and the minimum dV. Rd_i is a Ranking discount factor for need i. This value comes from the motivational ranking (Rd = 0.2 * ranking value), so the higher the priority of a homeostatic system, the lower the raking discount applied to its associated need.

Thus, when two vectors representing motivational tendencies are compared and both have the same magnitude (urgency of the need), the action selected will be based on the priority principle. However, if the need with lower priority has a higher urgency, the action selected could be based on this second need.

7.2. The sand-diving lizard benchmark.

To assess the performance of the allostatic control model proposed in this work, we aim to replicate the adaptive behaviour of the sand-diving lizard with a mobile robot within a similar ecological context.

First, we plan to extend the current implementation by incorporating several homeostatic systems. However, in order to adequately replicate the sand-diving lizard's behaviour, an experimental setup that captures the key features of its natural environment is also needed. In this setup, temperature varies according to a day/night cycle, being colder at night. Because diving behaviour is difficult to implement on a mobile robot, it will be substituted by a retreat behaviour towards a simulated burrow, where the robot can benefit from softer changes in temperature and safety from predators. Water and food sources are also allocated within the explorable space. Finally, a door allows the appearance of a predator. As in the presented experiment, the different stimuli will be represented by fiducials, except for temperature that will be represented by ambient light. Finally, our model will be extended by integrating a model of hippocampal place-cells to drive the navigation of the robot. Consequently, replication of the sand-diving lizard will come together with the replication of [9].

8. Discussion

In this paper, we propose an allostatic control model for regulatory behaviour that integrates insights from psychology and neuroscience. The model is inspired by the role of the Reticular Formation, a region of the brainstem in charge of controlling generalized CNS arousal and regulating action selection. The model also takes into account in its design recent theoretical and empirical work that update and extend the Maslow's hierarchy of needs. We have tested a first implementation of the homeostatic control layer of the model on a mobile robot and presented its preliminary results. Future work will extend the current implementation with the complete allostatic control model outlined in this paper.

Previous cognitive architectures have tried to model regulatory behaviour based on homeostatic and allostatic principles. For instance, DAC-X integrated homeostatic and allostatic principles in its reactive layer of control, reaching simulation of foraging behaviour [16]. However, this regulatory behaviour was inspired by hypothalamus functioning and previous work such as [9]. Hence, integration of the model presented in this paper in a cognitive architecture as DAC not only is supported by evidence but also release the model from navigation-specific implementations.

The outlined model, however, still presents several limitations. First, mRF is dependent and interconnected with other brain structures implicated in regulatory behaviour. Therefore, state-of-the-art literature about these areas, such as superior colliculus and hypothalamus, needs to be reviewed in order to understand how they can be integrated into our current model. Second, as it is currently defined, the vector approach for modelling emotional expression cannot disambiguate if a homeostatic dysregulation is caused by absence or excess. For instance, the regulatory behaviour of the sand-diving lizard is different if it arises in respond of excess or deficit of temperature.

In conclusion, by bringing together evidence coming from empirical and theoretical research we aim to develop a biologically inspired cognitive architecture that extends beyond the current state-of-the-art on allostatic control.

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