Ashby's Mobile Homeostat

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Abstract. In *Design for a Brain*, W. Ross Ashby speculates about the possibility of creating a mobile homeostat "with its critical states set so that it seeks situations of high illumination." This paper explores an embedding of Ashby's homeostat within a simulated robot and environment, exploring the question as to whether the classic (unmodified) homeostat architecture is able to adapt to this environment. Remaining faithful to the physical design of Ashby's device, this simulation enables us to quantitatively evaluate Ashby's proposition that homeostasis can be achieved through *ultrastability*. Following his *law of requisite variety*, increasing the number of units increases the time taken to reach equilibrium, and conversely, reducing internal connectivity reduces the time taken to reach equilibrium.

Keywords: Homeostat, Ultrastability, Robotics, Ashby

1 Introduction

Attendees of the ninth Macy Conference on Cybernetics in 1952 were presented with an account of an astonishing machine called the homeostat [1]. Completed in March 1948, its inventor was W. Ross Ashby, Research Director at the Barnwood House Hospital in Gloucester. The homeostat comprised four identical units constructed from ex-RAF bomb control switch-gear kits, each one refashioned into an electro-mechanical artificial neuron. The four units were identified by the colours red, green, blue, and yellow[1]. It allowed Ashby to demonstrate his principle of *ultrastability* and the *law of requisite variety*. The homeostat's most challenging feature which many found counter-intuitive, was its bias towards inaction. It was no wonder then, that Cyberneticist Julian Bigelow famously asked, "whether this particular model has any relation to the nervous system? It may be a beautiful replica of something, but heaven only knows what."

A contemporary of Ross Ashby (and fellow member of the Ratio club [14]) was W. Grey Walter, inventor of some of the very first autonomous robots, who likened the homeostat to a "fireside cat or dog which only stirs when disturbed, and then methodically finds a comfortable position and goes to sleep again" leading him to describe the homeostat as *Machina sopora* [2]. Walter was

[1] W. Ross Ashby journals, vol.12, p2747, February 1950.

contrasting the behaviour of the homeostat with his own Machina speculatrix which exhibited a more lively, exploratory behavior, "a typical animal propensity is to explore the environment rather than to wait passively for something to happen." Yet, the explorations of M. speculatrix would be all for nought in the face of a fundamental change in their environment that threatened the very survival of the robot. An organism cannot simply ignore such extreme conditions, but must act to remedy the cause of the problem. Franchi [3] traces these ideas back to Sigmund Freud's Project for a Scientific Psychology [4], "The organism cannot withdraw itself from [the major needs] as it does from external stimuli." In a fickle environment the homeostat comes into its own. When its essential variables are threatened it reconfigures itself at random until it hits upon a configuration that restores equilibrium in its new environment. Ashby's innovation is the double feedback loop, augmenting the conventional sensorimotor loop, that models how the environment impinges on the organism's essential variables. This is adaptation through *ultrastability.*

As described in *Design for a Brain* [5], the most distinctive features of the homeostat are the indicator needles that sit atop each unit and provide the output. There are a number of inputs plugged into each unit and their effect on the needle is modulated by a combination of a potentiometer and commutator to change the magnitude and polarity of the input voltage. A so-called *functionator* sums these weighted inputs to deflect the needle from its central position, "The position of the needle provides a beautiful functionator to get a linear function of the inputs."[2] The input weights may be switched under the control of an electro-mechanical uniselector from which a selection of (25) resistances and polarities may be chosen at random. This selector not only affords plasticity in weighting but also in connectivity, "Zeros occur, and when this happens the units are, in effect, cut off from one another" [1]. One of the inputs to the unit is a feedback loop from its own output, which may only be controlled manually. Negative feedback loops create oscillations that are the source of the dynamic behaviour in the homeostat. All the experiments in this paper are conducted with negative feedback.

The needles are integral to the function of the homeostat. They pick up a small electrical potential from a vane that dips into a trough of water, proportional to their deviation from the central position. The movement of the vanes through the water also provides a useful dampening effect. The linear equations of the homeostat are defined in the appendices of *Design for a Brain*[3]. Equation 1 assumes the existence of four units ($i = 1, 2, 3, 4$), as in the physical homeostat.

$$\begin{aligned} \frac{dx_i}{dt} &= \dot{x}_i \\ \frac{d\dot{x}_i}{dt} &= h(a_{i,1}x_1 + ... + a_{i,4}x_4) - j\dot{x}_i \end{aligned} \tag{1}$$

[2] W. Ross Ashby journals, vol.9, p2095, December 1946.
[3] Design for a Brain, 2$^{\text{nd}}$ revised edition, p246.

The variables x_j represent the outputs of the four homeostat units. The signed weights a_{ij} combine the potentiometer and commutator settings. The factor h controls the force on the needle, and j is the ratio of the viscosity of the fluid in the trough to the moment of inertia of the magnet, controlling the rate of change. The needles were also used by Ashby as input devices, as can be seen in his frequent interventions, physically displacing a needle one way or the other.
These equations are used to reproduce an experiment from Ashby's *Design for a Brain*[4]. This experiment describes an interaction between two homeostat units as illustrated in figure 1. Unit 1 represents an essential variable with bounds $[-1, 1]$, while unit 2 is under manual control. The output of unit 1 indicated by the solid line shows how the system adapts to the manual interventions visited upon unit 2. A manual deflection is applied to unit 2 throughout the experiment. This is held at 0.2 except at the deflection points D1 & D2 when it is raised to 0.3. After an initial settling time (from $t = 0$) the units adjust to the baseline deflection. At point D1 ($t = 50$) the deflection of unit 2 is briefly raised to 0.3 (dotted line) and unit 1 can be seen to follow in the same direction (solid line). After D1 the deflection is returned to the baseline. Without this baseline the magnitude at R1 would be zero and the reversal of polarity would have no effect. At point R1 ($t = 100$) the sign of the weight on the input from unit 1 to unit 2 is reversed under manual control. This in turn causes instability in unit 1 that transgresses the bounds of the essential variable, causing a step-change in the weights connecting unit 2 back to unit 1. Now, when the same deflection is applied at D2 ($t = 150$) the response of unit 1 is to move in the opposite direction. The manual reversal in unit 2 at R1 has been balanced by an automatic weight reversal in the selector of unit 1.
A MATLAB simulation reproducing this scenario is included in Appendix 1. The parameters are set as follows: $h = 1.0$, $j = 1.0$, with negative feedback on each unit of -0.5. The weight from unit 1 to unit 2 is initially -0.1, reversed at R1. The weight from unit 2 to unit 1 changes from 1.0 to -0.668, a value drawn from observation of the full homeostat simulation and known to result in a stable solution. Like other simulations [7][8] the aim is to capture the key features of Ashby's homeostat including the linear equations of Equation 1, essential bounds on variables giving rise to random step functions over the parameters, and environmental coupling consistent with the architecture of the homeostat. The full simulation is based on Euler's forward method which provides a rapid iterative approach that lends itself to solving differential equations in real-time. For this experiment, the bounds of the essential variables are defined as the range $[-1, 1]$.
The mathematical model presented above assumes a linear relationship between the inputs and the visible output, but in the physical embodiment of the homeostat it is (approximately) linear only in the range $\pm 45°$ either side of the needle centre. As Ashby notes, the system may be "unstable and self-aggravating, running away to the limits of the troughs." When the needle hits one of the end-stops of the trough, the needle can move no further and

[4] Design for a Brain, 2nd edition, section 8/4.

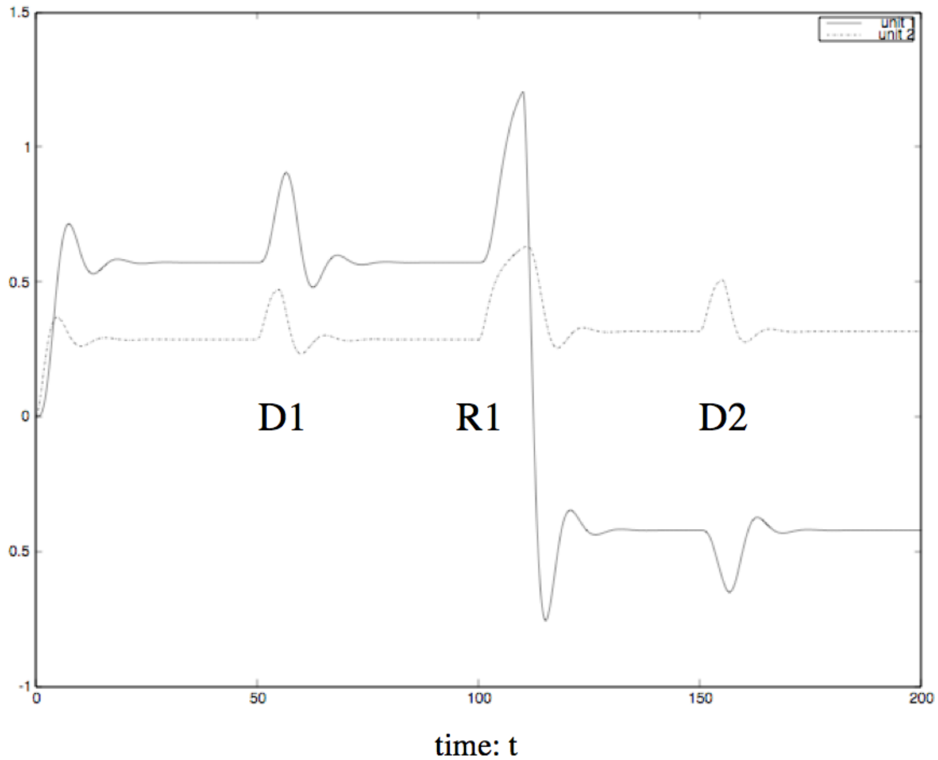

Fig. 1. Two units interacting. Identical deflections applied at D1 and D2 to unit 2 (dotted line) have opposite effects on unit 1 (solid line) after polarity reversal at R1 and subsequent recovery of stability.

thus the output *saturates* at that value. This is a classic saturating linear function. The full simulation models this effect, with the outputs saturating at the points of low and high potential.

2 The Mobile Homeostat

In *Design for a Brain*, Ashby tantalisingly mentions the possibility of constructing a mobile homeostat as a thought experiment, "Suppose U is mobile and is ultrastable, with its critical states set so that it seeks situations of high illumination." The homeostat as demonstrated by Ashby never was mobile, and the four variable machine represents within itself both organism and environment, brain and anti-brain together[5]. A mobile homeostat must be configured to interact with its external environment via appropriate transducers.

[5] W. Ross Ashby Aphorisms, "Every brain is also an anti-brain.", <http://www.rossashby.info/aphorisms.html#brain>

Like other researchers in this field [8][10][11][12], I have used the Braitenberg vehicle as an idealized platform in which to study the embodied homeostat brain. In 1984, neuroscientist Valentino Braitenberg published a small but influential book outlining a series of thought experiments that develop simple wheeled robots displaying increasingly sophisticated behaviours [9]. Each Braitenberg Vehicle has light sensing eyes, and is adapted to its simple environment containing mostly light sources to or from which they are variously attracted and repelled. Vehicles 1 to 5 develop the concepts of 1) motility; 2) tropisms; 3) excitatory and inhibitory synapses; 4) non-linearity; and 5) the logical possibilities of recurrent connections. With vehicle 6, we are invited to imagine these vehicles roaming the finite surface of a kitchen tabletop. Vehicles that wander too far away from the warming light source at the centre of their tabletop universe are greeted with nothing more than a precipitous fall to their doom, from whence they are recycled for their parts. Braitenberg considers the possibilities of stochastic and evolutionary approaches to developing vehicles that adapt and survive in this environment. Ashby's homeostat provides a baseline against which alternative approaches may be judged.

Franchi's research [10] considers a type 1 Braitenberg Vehicle with a single motor that can run forwards or backwards. This motor is controlled by a single homeostat unit. The robot inhabits a 1-dimensional world that presents a light-gradient to a single cyclopic eye. The single essential variable favours a band of high illumination and consequently the vehicle will eventually come to rest or achieve a dynamic equilibrium (oscillation) within this region. Independent control of a two-wheeled vehicle requires at least two homeostat units, one for each motor. This vehicle will live in a 2-dimensional plane with the light source at the centre of its world. It is equipped with a pair of directional eyes that can sense its position relative to this light source.

The homeostat contains a set of variables that may represent measurements made in the environment or within the reacting organism itself. The first step is to identify these variables in the simulation. Starting with the environment, the eyes detect the position of the robot relative to a single light source. Physiologically, our eyes have a logarithmic response to light that compensates for the fall in intensity due to the inverse square law. Ignoring distance then, each eye returns the cosine of its angle of incidence with the light source. The output of the eyes is therefore a pair of sine-waves at $90°$ to each other defining the angular position of the robot relative to the light source. Another variable in the environment is the distance from the light source. This is not detected directly by the eyes, but can be thought of as comparable to sensing the warmth of the sun. Within the simulated robot chassis there are two motors, each connected to a separate unit. As motors can be run backwards as well as forwards the speed of the motor is represented by a number in the range $[-1, 1]$. These motor variables are the only way in which the robot can act on, or react to, the environment.

The simulated environment is based on a simple kinematic model for 2-wheeled robots[13] where the robot's position and angle are expressed as a function of

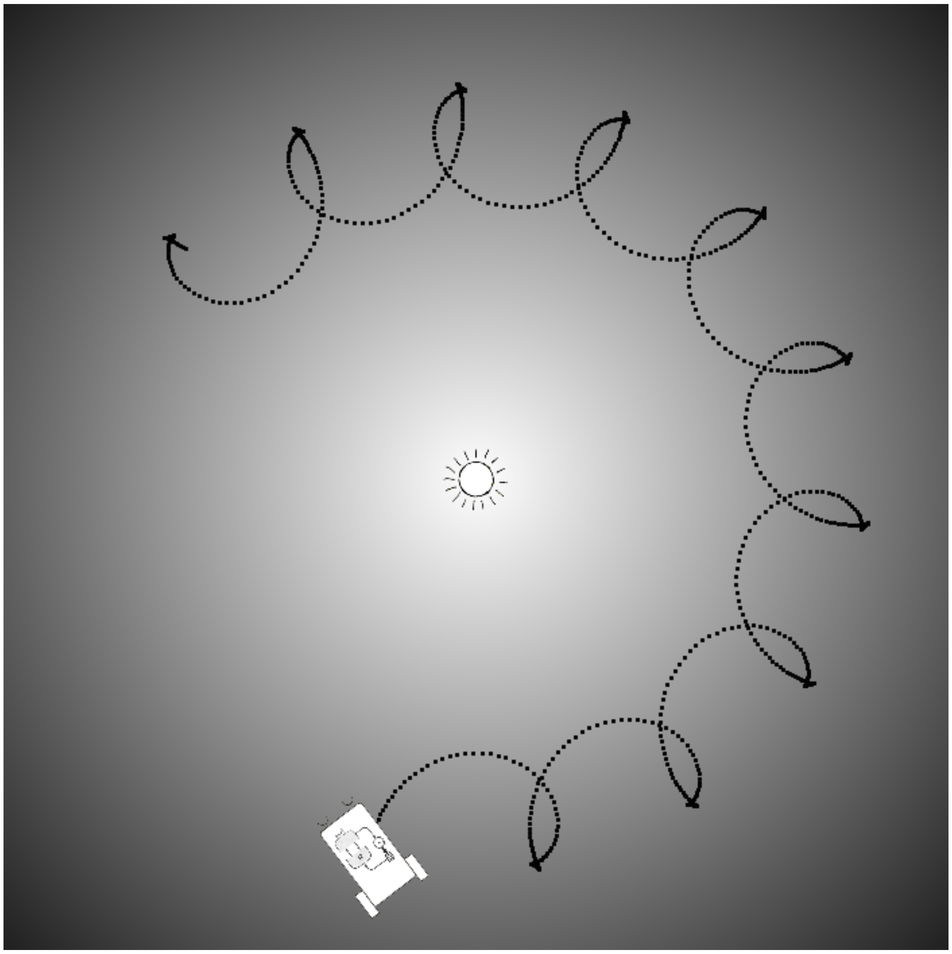

Fig. 2. A simulated mobile homeostat in a 2-dimensional environment with a central source of illumination. The trajectory of an adapted robot is plotted as a series of points.

the left and right motor variables. The robot turns using differential steering described by a differential equation for the change in angle with respect to time. The robot's velocity is the average of the two wheels, so its coordinates change as a function of velocity and angle. We find that a classic 2-unit homeostat is able to adapt to this environment. This is to be expected because it is possible to construct by hand, type 2 & 3 Braitenberg vehicles of similar complexity. A wide range of behaviours that achieve stability are possible, including straightforward orbital motion and the epicyclic trajectory of figure 2 showing actual output from the simulation.

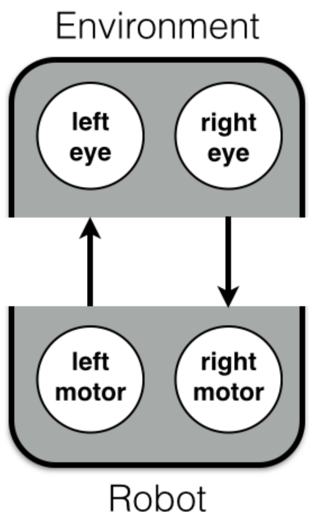

Fig. 3. Variables in the environment and in the robot. The arrows represent a multiplicity of connections representing the sensorimotor loop.

The simple sensorimotor loop embodied by a two-wheeled robot is illustrated figure 3. This diagram highlights the sensorimotor loop between the environment and the organism defined as the reacting part. The mobile homeostat will, in this case, comprise the two motor variables. The accessible variables in its environment correspond to its sensors and the variables essential to its survival.

Ashby's secondary feedback loop acts directly on the variables essential to the survival of the robot, namely the distance from the light source, which is inversely correlated with the proximity of the edge of the table. Whereas the robot can directly control the variables that represent the motor speeds, it can only indirectly influence the essential variables. By affecting a favourable trajectory through the world, its goal is to bring these essential variables under control. In other words, it can only influence its essential variables, and the values of all its sensors, by acting on them through the environment.

The mobile homeostat is configured along the lines of Ashby's machine with input, as described in *Introduction to Cybernetics*[6]. Each external input is identified as a parameter. For a set of n internal variables x, and a set of m parameters a, the state-determined system is described by a set of functions[6].

The mobile homeostat will have $n = 2$ internal units, one per motor. Each homeostat unit receives input from every other unit, including feedback from itself, and an additional $m = 3$ parameters, giving each simulated unit $m + n$

[6] Design for a Brain, 2nd revised edition, p262.

inputs ($i = 1, ..., n$).

$$\frac{dx_i}{dt} = f(x_1, ..., x_n, a_1, ..., a_m) \tag{2}$$

The architecture of the homeostat, intended as a static demonstrator, does not readily lend itself to hooking it up to essential variables in the environment. Each unit is self-contained in that when the needle hits the end of the troughs and the relay closes then the coils of the selector for that unit only are activated. The only global control is the frequency at which the relay is enabled, which Ashby judged should be somewhere between 1 and 10 seconds. Thus the relay represents the essential variable for a single unit only. There is no obvious mechanism by which the uniselector in separate units can be activated via a common signal.

Ashby comes to the rescue in his description of the 'fully joined system' where he describes a setup with "three essential variables ...all affected by the environment, and all able to veto the stability of the step-mechanisms S."[7] This many-to-one relationship can only represent a configuration where the essential variables are external parameters to a set of step-mechanisms. In the case of our mobile homeostat, a single environmental variable representing the robot's distance from the light source is input to the robot as a parameter, as are the sensor inputs. There is a channel from this parameter to both of the robot's internal variables by which their stability can be vetoed. This configuration is shown in figure 4.

This power of veto can only be ensured if the parametric input from the essential variable remains under manual control. If this were placed under control of the uniselector it would simply be able to disable the threatening input rather than adapting to it. It would be akin to the robot choosing to ignore pain rather than rectifying the cause of the pain. The veto signal needs to come as a short sharp shock so that it doesn't unnecessarily interfere with the stable fields of the internal variables. The distance is initially represented linearly in the range $[0, 1]$, the value supplied as a parameter is the output of a (Heaviside) threshold function that only triggers when the distance reaches 1. This prevents the distance having an undue effect on the main variables (that otherwise significantly increases the time required to reach stability). This veto signal is sufficient to drive both units into their critical regions causing the uniselectors of each unit to be activated at the point where the mobile homeostat falls off the edge of the world.

2.1 Ultrastability

The first experiment is to verify that the mobile homeostat coupled with this environment produces stable solutions within a reasonable time-scale. Each sample is the number of trials required to achieve a stable solution. The length of a trial is defined to be the time period after which the essential variables are checked for being within their bounds. Ashby suggested that essential variables

[7] Figure 11/10/1 Design for a Brain, 2^{nd} revised edition.

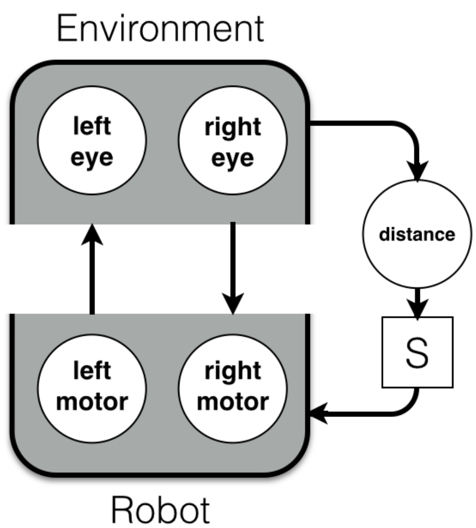

Fig. 4. Secondary feedback loop, where the environment acts on essential variables, is necessary for ultrastability. The essential variable influences the behavior of the robot via parameters S.

are not checked continuously, but perhaps every 3 seconds or so, the value used for these experiments. Robots that remain stable (with no selection events) for a full minute (20 trials) are deemed to be stable solutions (the 20 stable trials are subtracted from the total). Each test contains 100 independent samples initiated at a random position and parameter configuration. The data are merged and ranked so that the mean ranks may be compared.

Table 1. Ultrastability in 2,3,4 variables

Variables	2	3	4
sample size	100	100	100
mean rank	23.64	46.12	80.74

Table 1 captures the results for 2, 3, and 4-unit homeostats. We stop at four simply because that's how many units the original homeostat contained, but also the direction the results are headed is pretty plain to see. Each is a fully-joined system such that every unit of the homeostat is fully (and bi-directionally) joined with every other. Firstly, we note that the 2-unit homeostat does indeed produce stable solutions. Ashby's law of requisite variety states that a control system need have no more variety than the environment it controls. Furthermore, he predicted that as we add additional redundant units then the required adaptation time would increase. Given that

2-units are demonstrably sufficient to control the robot in this environment, in the experiment with 3 and 4 units we expect to see an increase in the time taken to reach stability.

The results follow a geometric distribution so a non-parametric Kruskal-Wallis analysis of variance (H-test) is used to compare the mean ranks of the three sample sets. Under the null hypothesis the mean ranks of the three sample sets are the same. For at least a 95% degree of certainty ($alpha = 0.05$) with $k(groups) - 1 = 2$ degrees of freedom the H critical value is 5.991. The H-statistic is calculated to be $197.85 > 5.991$ therefore there is a significant difference between the mean ranks of the three groups with varying number of homeostat units (at least two of the sample sets differ). With a mean rank score of 23.64 for 2-units, 46.12 for 3-units, and 80.74 for 3-units, this indicates that the time taken to reach stability increases with the number of (redundant) units.

3 Reducing Connectivity

Ashby observed that while the fully joined system retains generality, it would be an impractical solution in reality. Real organisms exploit constraint in the world by limiting their own internal connectivity where it is not needed. First and foremost, this is a property of the environment. Only if there are constraints in the world such that the environment is not fully connected, can the homeostat exploit this by reducing its own internal connectivity.

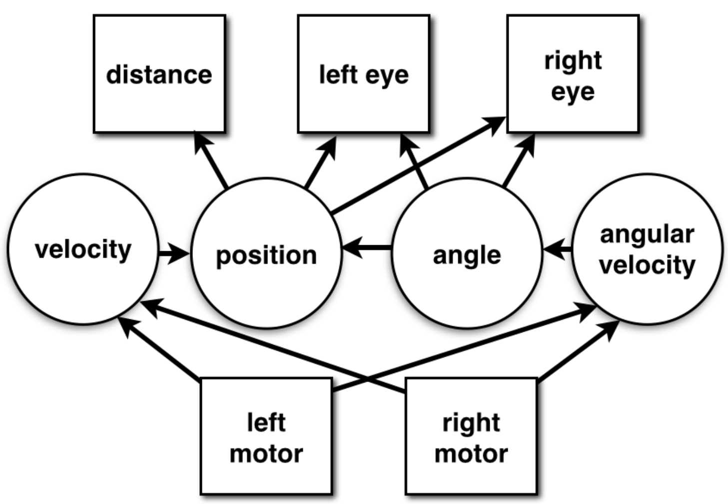

Fig. 5. Diagram of Immediate Effects showing constraint among environmental variables and parameters to/from the homeostat.

The diagram of immediate effects for the simulated environment is illustrated in figure 5. This captures additional variables that are part of the simulated environment but are not parameters to the robot. For example the robot cannot directly sense its absolute position or angle. The left and right motor values are the two main variables of the robot and are parameters (square boxes) of the environment, while the distance, left and right eyes are input parameters to the robot. There is considerable constraint in this environment. For example, the values of the eyes are independent of the distance given the position of the robot. Nor are there any recurrent connections.

Ashby's counter-intuitive thesis is that "coordination can take place through the environment; communication within the nervous system is not always necessary." This can be tested in the mobile homeostat by severing all connections between the two halves of the 2-unit homeostat brain. Both units still receive all the available input parameters and their recurrent inputs. This is achieved in the homeostat by switching just those severed connections to manual control and setting their weights to zero. The effect of this is to reduce the variety of the system towards that of the environment.

If this is a cut too far then there will be no stable solutions. However, the hard-wired neural circuits of Braitenberg's Vehicles 2 and 3, with crossed and uncrossed channels between eye and motor, demonstrate the workability of low-connectivity adaptations to this environment. The mobile homeostat with disjoint variables includes this space of simpler vehicles while excluding more complex models with internally recurrent networks. There is *no direct connection* between the two main variables of the disjoint homeostat, but they may still influence each other indirectly through the environment.

Table 2. Ultrastability in 2 variables with varying connectivity

Variables	2 (disjoint)	2 (fully joined)
sample size	100	100
mean rank	37.27	63.23

The data for the system of two fully-joined (bidirectionally connected) variables from above is compared with a system of two internally disjoint variables. The results are shown in table 2. To compare the two sample sets both with 2-units but with different internal connectivities, a non-parametric Mann-Whitney (U-test) for large sample sizes is used to determine whether the two samples are drawn from different populations. Under the null hypothesis the mean ranks of the two sample sets are the same. A one tailed test is used because the time taken to reach stability is expected to increase with the number of units. For a 95% degree of certainty ($alpha = 0.05$) the critical value of Z for a one-tailed test is -1.645. In this case, with a calculated Z score of $6.34 > 1.645$, we can state with 95% certainty that there is a difference between the two groups. Reducing internal connectivity reduces the time taken to reach stability.

3.1 Discussion

While these experiments demonstrate that the classic homeostat architecture is able to control a robot in a two-dimensional space, they also highlight a shortcoming in the way that the essential variables are connected to the environment. The distance input must be artificially forced through both main variables in order to trigger the essential limits on those variables. Ashby noted this weakness in his journal, "In the homeostat, further variables are put between the environment and the essential variables (the relay). The relay thus never 'sees' the environment directly."[8] This arrangement is the equivalent of building a protective shell around the essential variables rather than employing intelligence to avoid a threat. Ashby experimented with eliminating this one-to-one connection between the main and essential variables in the homeostat[9] by switching out the relay and placing the uniselector under manual control.

Experiments with decoupling the essential variables from the main variables serve to highlight another early postulate of Ashby, the *equivalence of levels*, "all levels are equivalent for the formulation of the general laws of psychology"[10]. In decoupling the essential variables from the motor variables and slaving them only to the essential variable representing distance, the unintended result was that these variables inevitably get stuck at saturation (full forward or full reverse). These stuck variables create a wall of constancies that render the robot unreactive. The conclusion is that homeostasis is indeed necessary at all levels from individual internal variables, to essential variables directly exposed to the environment.

A theory of how the essential variables might be re-connected did not begin to emerge until the design of the DAMS (Dispersive and Multistable System), putting it beyond the scope of this paper. According to Ashby, "This picture must be used if any severe test of a reacting system (artificial brain) is to be applied."[11]

3.2 Conclusion

This research extends previous work in applying the classic homeostat architecture to the problem of controlling a robot in a simulated two-dimensional environment. This is inspired by Ashby's thought experiment of a mobile homeostat seeking situations of high-illumination. This experimental setup allowed us to explore the principle of *ultrastability*, Ashby's *law of requisite variety*, and the effects of increasing the number of units or decreasing connectivity.

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[8] W. Ross Ashby journals, vol.12, p2960, August 1950.
[9] W. Ross Ashby journals, vol.12, p2748, February 1950.
[10] W. Ross Ashby journals, vol.1, p40, 1928.
[11] W. Ross Ashby journals, vol.12, p2962, August 1950.

4 Appendix: MATLAB model for figure 1

```
function i = inputs1(t)
 # return a row vector of inputs over time (deflection)
 # deflection at D1, D2
 if ((50<t && t<55) || (150<t && t<155))
    i = [0.3];
 else
    i = [0.2];
 endif
endfunction

function w = weights1(t)
  if (t<100)
    # three rows: unit 1 output; unit 2 output; deflection
    # two columns: unit 1 input, unit 2 input (manually controlled)
    # each unit has fixed negative feedback -0.5
    # initial 1->2 weighting -0.1 reversed at R1
    # deflection effects unit 2 with weight 1.0
    w = [-0.5, -0.1; 1.0, -0.5; 0.0, 1.0 ];
  elseif (t<110)
    # reverse commutator on input to 2nd unit (1->2) at R1
    w = [-0.5, +0.1; 1.0, -0.5; 0.0, 1.0 ];
  else
    # uniselector selects new weights on 1st unit (2->1) post R1
    w = [-0.5, +0.1; -0.668, -0.5; 0.0, 1.0 ];
  endif
endfunction

function xdot = h1(x,t)
  h = 1.0; j = 1.0;
  # multiply inputs by weights, a
  xa = [x(1:2)',inputs1(t)]*weights1(t);
  # output (xdot) represents x1, x2, x1', x2'
  xdot(1) = x(3);
  xdot(2) = x(4);
  xdot(3) = h*xa(1) - j*x(3);
  xdot(4) = h*xa(2) - j*x(4);
endfunction

t=linspace(0,200,1000)
x0 = [0;0;0;0]
x = lsode("h1",x0,t)
plot(t,x(:,1),"-;unit 1;k",t,x(:,2),":;unit 2;k");
```

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