Entrainment as a paradigm for modelling a planetary robot's circadian rhythm

Claire Rocks(1), Dave Barnes(1)

(1)Department of Computer Science
University of Wales, Aberystwyth
Penglais, Aberystwyth
SY23 3DB, United Kingdom
Email: clr02@aber.ac.uk

ABSTRACT

The Aurora Project aims to create and implement a European long-term plan for the exploration of the Solar System, culminating in a human expedition to Mars by 2030. Recognised steps along the way include the robotic exploration of Mars and a robotic outpost. Necessary to autonomous robotic missions is activity coordination with the day-night cycle. This paper describes work undertaken as part of a research project looking at using the phenomenon of entrainment as a means of generating a robotic circadian rhythm that will adapt as the day changes due to changing seasons or changing global position. This work is aimed at increasing robot autonomy without the need for explicit programming. It is based upon a model of the human sleep-wake cycle proposed by Gander et al [1][2]. The model is comprised of two coupled Van-der-Pol oscillators that represent the internal rhythms within the body, they are acted upon by a sinusoidal stimulus representing the external day-night cycle. The phase of the external stimulus was either advanced or delayed by 1 hour, 5 hours and 10 hours and the re-entrainment of the oscillators was observed. The results show that the time taken for the system to re-entrain depends on the magnitude of the phase advance or delay. Proposed future applications to space robotics are also discussed.

INTRODUCTION

Entrainment is "the adjustment of rhythms of oscillating objects due to their weak interaction [3]". Systems where we see the entrainment of living things are abundant in nature from thousands of fireflies that flash in unison to pacemaker cells in the heart, and almost all species exhibit daily changes in their behaviour or physiology synchronised with the day/night cycle. What controls these changes is a circadian clock. Robots intended for space missions often undergo many activities scheduled by a complex time series determined by their local day-night cycle. This work seeks to provide a means by which the execution of tasks in synchrony with the local environment can be automatically updated as the day-night cycle changes with the seasons or due to the rover’s locomotion and hence change in global position.

Much research has been undertaken into the mammalian circadian clock including research into subjects in time isolation, with no cues from the day-night cycle [4][5][6]. This research has shown that the circadian rhythm is not simply a response to the day-night cycle but exists in the absence of one, therefore rises from some form of timekeeping within the organism, it is a self sustained oscillator. Subjects were also shown to have different periods in their temperature rhythms and their activity rhythms. The rhythms that run in the absence of day-night cues are called free running rhythms, they are found to be approximately 24 hours, but not exactly. However, these rhythms do have the ability to be entrained by external stimuli to give rise to the 24-hour period. The most important of these stimuli is the day-night cycle caused by the rotation of the Earth.

The ability to entrain enables organisms to coordinate their activities to the day-night and to re-synchronise with changing seasons; it also enables them to adjust to new time zones. This ability would be useful to a planetary robot, it could synchronise its activity schedule on landing and remain synchronised with the local environment as it moved around the planet.
METHODS

The proposed robotic circadian rhythm is based upon a model of the human sleep-wake cycle proposed by Gander et al [1][2]. The model is comprised of two coupled Van-der-Pol oscillators that represent the internal rhythms within the body. They are acted upon by a sinusoidal stimulus representing the external day-night cycle. A Van der Pol oscillator is an example of a non-linear self-sustaining oscillator; they have also been used to model the heart [7] and intestinal tracts [8]. The oscillators are described by (1), (2) and (3).

\[
k^2 \frac{d^2 x}{dt^2} + k \mu_x (-1 + x^2) \frac{dx}{dt} + \omega_x^2 x + F_{yx} k \frac{dy}{dt} = 0
\]

\[
k^2 \frac{d^2 y}{dt^2} + k \mu_y (-1 + y^2) \frac{dy}{dt} + \omega_y^2 y + F_{yx} k \frac{dx}{dt} = F_y z
\]

\[
z = \cos \frac{\omega_z t}{k}
\]

\(k\) is a time parameter equal to \(24/2\pi\) and is used so that the unit of the period of oscillation is Earth-days. \(\mu_x\) and \(\mu_y\) represent the stiffness of the oscillators \(\approx 0.1\). The value of \(\omega_z\) is chosen to represent the specific time period, so in this form an Earth day has a value of 1.0, and for an approximate Martian day a value of 0.973 is used and so on.

The \(x\) oscillator, described by (1) is the dominant oscillator and is thought to drive the temperature cycle. It has a much larger effect on \(y\), described by (2), than \(y\) has on it. The \(y\) oscillator is the sleep/wake or activity oscillator. The \(z\) oscillator, described by (3), represents the external stimulus. A sinusoid is the simplest form this stimulus could take, and although a natural light/dark stimulus would not be sinusoidal the exact waveform is largely immaterial because the non-linearity, or stiffness, of the other two oscillators is low [2]. The external stimulus acts only on the \(y\) oscillator. By entraining task oscillators to the central activity oscillator the duration of a task or the time at which it is executed can be updated automatically. This is shown diagrammatically in Fig. 1.

A precursor to robotic experiments using this model is the understanding of the phenomenon of entrainment, and how it applies in this case. Biologically plausible values for the natural frequencies of the temperature and activity oscillators, as well as the coupling were used. A simulation based on further work by Gander et al [9] either advanced or delayed the phase of a 24-hour external stimulus by 1 hour, 5 hours and 10 hours and the re-entrainment of the oscillators is observed. A method based on the Hilbert Transform [3] is used to obtain the instantaneous phases of each oscillator and the relationship between those phases.
RESULTS

Fig. 2 Phase differences between oscillators for (a) no advance or delay, (b) 1 hour phase advance, (c) 1 hour phase delay, (d) 5 hours phase advance, (e) 5 hours phase delay, (f) 10 hours phase advance, (g) 10 hours phase delay
The graphs show horizontal lines when the system is entrained and the phase differences are constant. Anomalies at the very beginning are due to the initial conditions and the simulation settling time.

Fig. 2(b) and Fig. 2(c) show the phase differences following a 1-hour phase advance or delay in the external stimulus, and the effect on the phase differences of the oscillators is very small (c.f. Fig. 2(a) where there is no perturbation) and the system re-enters quickly. Fig. 2(d) and Fig. 2(e) show the phase differences following a 5-hour advance or delay, the effect is greater than for the 1-hour delay and the system takes longer to re-entrain. Fig. 2(f) and Fig. 2(g) show the phase differences following a 10-hour advance or delay, the effect is greater still and the system takes even longer to re-entrain. However, all of the systems re-entrain within a couple of 24-hour cycles and all show the oscillator taking longer to re-entrain, this is expected as it is not influenced directly by the external stimulus, instead it is influenced through the oscillator.

CONCLUSION

The results show that the time taken for the system to re-entrain depends on the magnitude of the phase advance or delay but that the oscillators do all re-entrain given an external stimulus coupling strength of 2.0 (this represents a strong coupling to the external environment). The results show that the rhythms that will adjust in response to changes in the phase of the external day-night stimulus.

As entrainment and circadian rhythms are so ubiquitous in nature it seems intuitive to pursue how they might be applied to robotics to allow activity coordination with local environment stimuli, with a view to reducing the amount of explicit programming or terrestrial based intervention required, therefore reducing the level of computation needed without impacting on the level of autonomy.

FURTHER WORK

Once this model has been fully explored, the next step is to use this property of entrainment in an application useful in space robotics. Currently two options have been considered:

1. Autonomous Task Planning - by mapping activities, such as exploring, to other oscillators entrained to a central activity oscillator would mean that a schedule of events coordinated with the local day/night cycle could be generated. Employing a robot circadian rhythm gives the robot the ability to generate its own schedule of events and also adapt this schedule as it changes its latitude and longitude on the planet or as the seasons change, without the need to explicitly program this.

2. Cooperative Behaviour - Using a common circadian rhythm to coordinate activities provides coordination via the external environment, which is more robust than via an artificial signal. It also reduces the problem to many two-oscillator systems, and therefore should be scalable.

REFERENCES