A Navigating Rat Animat

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Abstract

This paper presents a new rat animat, a rat-sized bio-inspired robot platform currently being developed for embodied cognition and neuroscience research. The rodent animat is 150mm x 80mm x 70mm and has a differential drive, visual, proximity, and odometry sensors, x86 PC, and LCD interface. The rat animat has a bio-inspired rodent navigation and mapping system called RatSLAM which demonstrates the capabilities of the platform and framework. A case study is presented of the robot's ability to learn the spatial layout of a figure of eight laboratory environment, including its ability to close physical loops based on visual input and odometry. A firing field plot similar to rodent 'non-conjunctive grid cells' is shown by plotting the activity of an internal network. Having a rodent animat the size of a real rat allows exploration of embodiment issues such as how the robot's sensori-motor systems and cognitive abilities interact. The initial observations concern the limitations of the design as well as its strengths. For example, the visual sensor has a narrower field of view and is located much closer to the ground than for other robots in the lab, which alters the salience of visual cues and the effectiveness of different visual filtering techniques. The small size of the robot relative to corridors and open areas impacts on the possible trajectories of the robot. These perspective and size issues affect the formation and use of the cognitive map, and hence the navigation abilities of the rat animat.

Introduction

Brains are evolved to control bodies, which have characteristic sizes, and live in specific environments. One approach to studying embodiment is to develop animats (Wilson, 1991), which are robots that mimic specific animals that enable the study of the integrated system formed by brain, body and environment (Beer, 2008; Beer & Williams, 2009). Animats also enable comparisons with the behavior of the corresponding animal on similar tasks, which can lead to the co-development of animats with animal laboratory studies. No animat perfectly mimics their biological counterpart, and priorities need to be established for the animat design.

Bio-inspired robotics is a growing field that draws insights from nature's solutions for interacting with real-world environments. A major research question in bio-inspired robotics is the design and evaluation of effective algorithms for embodied learning and action. In particular, rodents have been well-studied both biologically and for bio-inspired technologies. Rodents have excellent mobility, and interactions are particularly important for survival both within peripersonal space (the space within reach of the animal) and wider aspects of navigation in geopersonal space (the space that the agent can move through beyond its current location). Rodents have proved an effective match between embodied ability, brain complexity and current state-of-the-art in neuroscience. Embodiment itself can reduce the complexity of control architectures and improve energy efficiency (Brooks, 1991).

Bio-mimicry is often used as a more targeted term to develop engineering solutions that not only develop algorithms based on animal morphology and behaviour, but also that aim to preserve a high fidelity with the target system. This research focuses on bio-mimicry which has the potential to benefit biology as well as engineering, as discussed in detail in the extensive article and commentaries in (Webb, 2000, 2001).

In robotics, a significant engineering design aspect is the tradeoff between size and capabilities. Capabilities include sensing, actuation and computation. For a rat animat the size is given by the real animal. However, it is not always possible to integrate the desired capabilities into an animat the size of the real animal. The robot can be designed with only those capabilities that fit into the size of the real animal, or the robot's size can be increased to accommodate the full complement of desired capabilities. Setting the first design requirement to be a match between the size of the robot and the animal enables the study of aspects of embodiment and the physical context that are not possible in larger animats.

Body size places strong constraints on an animat, just as it does on an animal's abilities, including its navigational abilities and the range of its behavior. Size is rarely given precedence in design criteria in embodied systems, but to test the rat animat on the same laboratory tasks as real rats, size becomes a defining feature in our research. Physical size places strong constraints on power available for movement and computational abilities. Size also impacts on possible physical sensori-motor configuration. For example, with respect to sensors, the visual field perspective is impacted by the height of the camera, and for motor control, the power of the motors and size of the wheels impact on the range and terrain that the robot can cover.

Existing robot rats can be broadly categorized from an engineering point of view into two categories: those with computational capacity equivalent to a standard PC but larger than a rat, and those the size of rat but with reduced or custom computational capacity. The recent availability of small x86 platforms (that allow a standard Windows or Linux OS) has allowed for a reduction in the size of robots without compromising on computational capacity. This paper describes a new rat animat that takes advantage of the recent miniaturization of PC equivalent computational parts to build a rat sized robot platform.

RatSLAM is a bio-inspired navigation system based on the rodent hippocampus, which uses visual appearance as the primary mechanism for localization (Milford & Wyeth, 2009). Previous studies have been performed on a robot where the visual sensor is approximately 0.5m from the ground. The rat's eyes are an order of magnitude lower at a height of approximately 0.05m above the ground. The nature and quality of information in different parts of the visual field is impacted by the location of the camera, and hence the perspective of the robot.

The next section reviews existing rodent animat platforms and rodent inspired navigation system. The following section describes the new rodent animat platform and the RatSLAM system. Then the paper describes the focus study for this paper where the rat animat maps a figure of eight environment. Then the results of the navigation studies, including the resultant topological map and 'place fields' are described. The final section provides discussion, including directions for future work, before the paper concludes.

Background

Robot rat studies to date have developed many components for building a rat-like robot, but either the size is much larger than a real rat, or the computational capabilities have limited low fidelity bio-mimicry. The AMouse (Fend, 2004) has two whisker arrays and an omnidirectional camera. The robot uses whiskers to ensure robust obstacle navigation in changing light conditions integrated into a subsumption architecture. The camera and whisker were separate modules added to the Khepera robot platform.

Psikharpax is a rat animat, with sensors, actuators and control architectures closely inspired by the rat (Meyera et al., 2005). Mechanically, the rat is 500mm long and has two wheels that allow a maximum speed of 0.3m/s. Psikharpax can rear and grasp objects with its foreleg and can move its head and eyes. The sensors include two visual sensors, an auditory system and a 32 whisker haptic system. A bio-mimetic chip capable of low-level real time signal processing for sensor fusion is under design. Recently an omni-directional visual system has been added (Lacheze, Benosman, & Meyer, 2008).

Alternatively, the Cyber Rodent project has less emphasis on physical bio-mimicry, rather taking its inspiration from neuromodulation (in particular dopamine, serotonin, acetylcholine and noradrenaline), and uses self-preservation and self-reproduction in a reinforcement learning framework to understand the biological reward system (Doya & Uchibe, 2005). The robot is larger than a typical rodent, 220mm long and weighs 1.75kg and has two wheels that allow a maximum speed of 1.3m/s. Sensors include a camera, range and proximity sensors, gyros and accelerometers, microphones. For communication the robot has a speaker and tri-color LED. Computationally, it has custom embedded hardware for on-robot learning.

There are a number of robot rats that are focuses on the embodiment of the whisker system (Fend, Bovet, & Pfeifer, 2006; Fox, Mitchinson, Pearson, Pipe, & Prescott, 2009; Pearson, Pipe, Melhuish, Mitchinson, & Prescott, 2007). These robots explore vibrissal sensory processing for texture discrimination, obstacle detection and wall following. A number of different sensors, whisker materials, whisker actuation methods and computational processing techniques have been explored.

Robot rats also interact with real rodents in a laboratory. Waseda Mouse-No.2 (WM-2) (1998) has a similar size and mass to rat, uses a fur coat to achieve a similar appearance and uses wheels for mobility. An embedded microcontroller handles sensors, motors and communication with the host computer over an IR link. They demonstrated that a real rat recognized the movement of WM-2, and that the robot influenced the rat's behavior, helping it to learn response to stimulations. WM-6 added arms at the front for interacting with levers (2006). WM-6 uses Bluetooth to communicate wirelessly with the host computer. Patanè, Mattoli et al. (2007) has increased the complexity of the interaction possible by using a legged robot rat. The host computer is responsible for autonomous control of the robot via overhead vision. The robot successfully taught the rat a lever pushing task to get food.

Rodent bio-inspired navigation

There has been extensive work investigating how animals navigate, in particular towards the goal of understanding how the rodent's hippocampus and associated regions work to localize, map and navigate an environment. These biological studies have formed the basis for many rodent-inspired robot navigation systems. Cells with a range of specific functions have been found including head-direction cells (Ranck Jr, 1984), place cells (O'Keefe & Conway, 1978), and grid-cells (Hafting, Fyhn, Molden, Moser, & Moser, 2005). There are several approaches to apply these insights to robot navigation ranging from those that try and mimic the biological studies as closely as possible to those that use them as inspiration but apply an engineering approach.

Early work by Mataric (1991) used a layers-of-competence subsumption architecture on a custom robot with sonar sensors. Burgess and Donnett et al. (1997) developed a simulation of neuronal place cells and "goal" cells to create mapping and navigation abilities on a K-Team Khepera robot. Meyer, Guillota et al. (2005) base their navigation system on place cells and behavioral system and are applying it to their large rat animat, Psikharpax, described previously. Alternatively, Arleo and Gerstner's (2000) approach more closely emulates biological place cells and was demonstrated using a K-Team Khepera robot in a small environment with artificial textures. Barrera and Weitzenfeld et al. (2008) demonstrated their biologically inspired spatially cognitive work in a typical wet lab experimental setting using a Sony AIBO. Milford and Wyeth (2009) focused on using place cell biology as an inspiration to engineer a complete robot navigation solution on an ActiveMedia Pioneer robot.

RoboRat platform

Given the research to date on rodent animats, there is an opportunity to integrate many of the existing ideas, extending them where necessary, and develop a robot rat-mimic which has the size and navigation abilities to operate in the same environments as real rats, challenged with the same tasks, and controlled by neural-inspired algorithms. Such a rat animat could be used to study embodiment issues in robotics, test theories of the neural basis of mammalian navigation, and also has the potential to open new areas of behavioral study through interaction with real rats. In this paper, we address the first goal, that of developing a rat-size robot to use as an integrated development platform.

A (real) rat is incredibly mobile and uses its legs, spine, head and tail to traverse complex environments. As shown in Fig 1 the prototype robot is approximately the size and mass of a large rat and mechanically simple using wheels for mobility. The robot's dimensions are 150mm long, 80mm wide, and 70mm high, not including the Wi-Fi antenna with a mass of 0.5kg approximating those of a real rat. Note that the cream colored body shown in the figure is designed to allow for evaluation of sensors and their locations and will be designed to incorporate aspects of the rat's body shape in subsequent development.

A real rat digests food for energy. The robot has a battery and on board recharging that allows two hours of continuous operation.

A (real) rat's eyes have poor visual acuity, high sensitivity that gives excellent performance in low light conditions, and a wide field of view. A custom solution is currently under development, designed to allow the robot to see well in low light conditions and over a wide field of view. For this study the prototype design uses a single low-cost USB webcam for the robot rat's vision sensor.

A rat has whiskers that can discriminate texture and sense proximity for close obstacle avoidance. This prototype design uses four Sharp IR range sensors arrayed at the front to give proximity information for obstacle avoidance.

A rat can integrate its self motion given by leg movement and vestibular information. The robot has encoders on the wheels which provide an estimate of the distance travelled.

A rat does all its thinking on-rat. On-robot computational capacity is given by a custom embedded controller coupled with a RoBoard mainboard with a 1GHz Vortex86DX CPU, 256MB RAM, and 4GB microSDHC card currently running Windows XP. The RoBoard has a wireless LAN connection so that it can communicate with other computers to gain access to additional computational capacity. A separate sensor and actuator interface controller handles the robot motion and reading sensors. This interface controller also has an LCD and navigation pad (similar to small portable devices) to allow user interaction.

The robot has a *distributed cognitive control architecture* (*DCCA*) that will support the testing of a range of neural models. In this context 'distributed' refers to modular, layered systems which can be implemented across physically separate computational platforms; 'cognitive' refers to neutrally-inspired or high-fidelity neural networks; and 'control' indicates that the robots operate in closed feedback systems. The DCCA is implemented using a robot software framework.

A robot server-client interface, *Player* (Gerkey, Vaughan, & Howard, 2003; Vaughan, 2008) is used as the basis for the framework. This framework allows studies in a real environment or in a virtual reality world simulation, allows pluggable modules for a variety of tasks, and connects to appropriate visualization tools. *Player* is free software that provides a client-server network interface that abstracts the robot hardware, sensors and actuators. This network interface allows for modularity and distribution of computation. *Player* has bindings for several different compiled and interpreted programming languages including: C, C++, Python, and MATLAB. The interpreted programming languages enable rapid prototyping and are commonly used by neuroscientists.

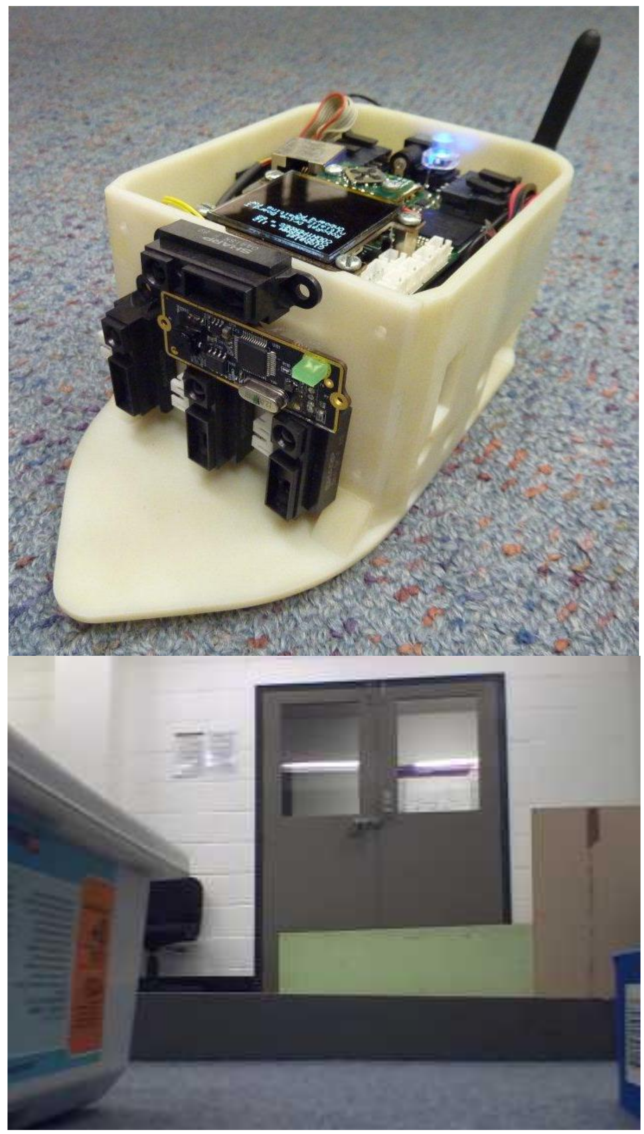

Fig 1. (top) The current state of the robot rat, showing the web camera, and four IR proximity sensors at the front, the Wi-Fi antenna 'tail' at the back and the LCD and navigation button user interface on the top. For this paper the left and right IR sensors were angled out at 45 degrees. (bottom) An image from the robot's camera sent over the wireless LAN as a 320 pixel by 240 pixel JPG image. Note the narrow field of view.

RatSLAM navigation

RatSLAM is a biologically inspired SLAM system based on models of mapping and navigation processes in the rodent hippocampus. RatSLAM contains three major modules; a vision system for appearance-based scene recognition, a neural network that represents the location and orientation state of the robot, and a graphical mapping algorithm that creates semi-metric topological maps. This section provides a brief overview of RatSLAM; a more technical system description can be found in (Milford & Wyeth, 2008, 2009).

Attractor Dynamics and Path Integration

RatSLAM represents the location and orientation state of the robot using a three-dimensional continuous attractor network (CAN). Continuous attractor networks are a popular method of modeling the spatially responsive cells found in the rodent brain (Arleo & Gerstner, 2000; Samsonovich & McNaughton, 1997; Stringer, Rolls, Trappenberg, & de Araujo, 2002; Stringer, Trappenberg, Rolls, & de Araujo, 2002). RatSLAM uses a rate-coded continuous attractor network. The network is arranged in a three-dimensional structure, where each of the three dimensions corresponds to one of the three spatial dimensions x', y', and θ' (Fig 2). Each cell is connected to nearby cells by both excitatory and inhibitory connections, which "wrap" across the opposing faces of the network structure. The connectivity is designed such that during robot navigation, the pose cell network will usually have a single cluster of highly active units, often referred to as an "activity packet" or "activity bump". The centre of this activity packet encodes the robot's location and orientation. Path integration is performed by shifting the activity in the pose cells based on self-motion information, such as wheel encoder counts. In a similar manner to the attractor dynamics, path integration can shift activity off one face of the pose cell structure, wrapping the activity around to the opposing face. Copying and shifting activity offers stable path integration performance over a wider range of movement speeds and under irregular system iteration rates, when compared with methods that shift activity through weighted connections (Arleo & Gerstner, 2000).

Local View Cells and Visual Pose Recalibration

The RatSLAM vision system learns a collection of visual templates representing what the robot sees at different locations in the environment. Each visual template is represented by a *local view cell*, which becomes active when the robot sees a visual scene similar to the template. To enable recalibration of the robot pose representation, connections are formed between co-active local view and pose cells. If the robot sees a familiar visual scene, the corresponding local view cell will activate, in turn activating the pose cells it is connected to. The activity packet will move towards the location associated with that visual scene, providing a means for correcting odometric drift and closing a loop.

Experience Mapping

The experience map is a semi-metric topological map driven by output from both the pose cells and local view cells. As a graphical map it contains representations of places, called experiences, and links between these experiences describing properties of the transition between them. Each experience is associated with a certain pose cell network state and local view cell network state, but exists in a separate co-ordinate space to the pose cell network, called experience map space. New experiences are generated when no current experiences sufficiently match the activity states in the pose and local view cell networks. A graph relaxation method distributes odometry errors throughout the map.

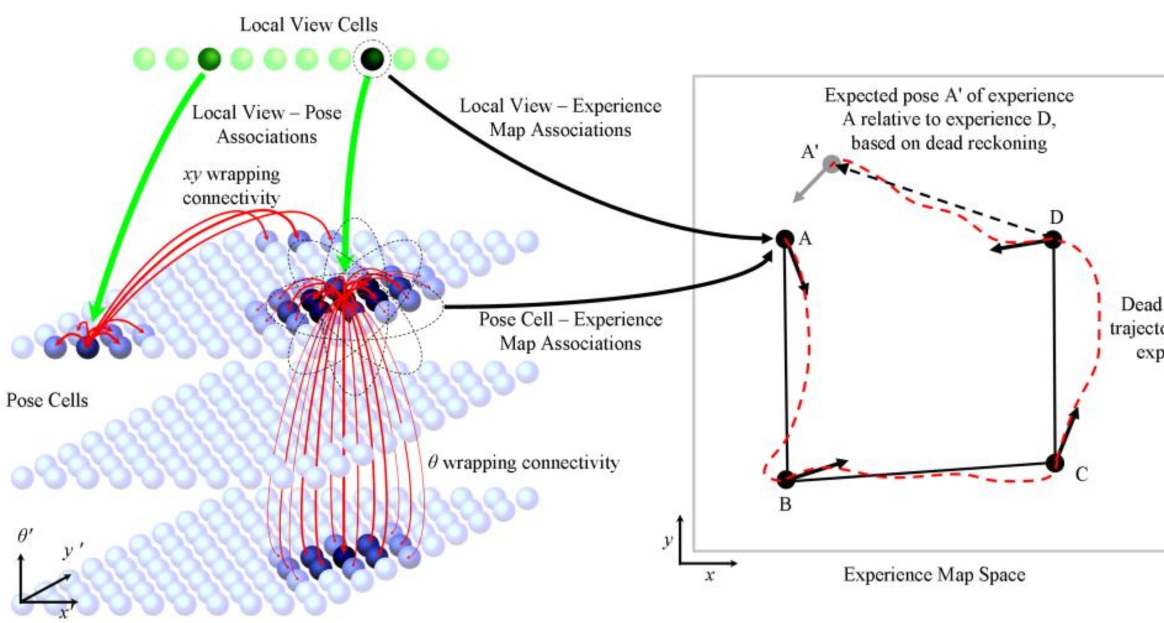

Fig 2. The RatSLAM system consists of the pose cells, which encode the robot's location and orientation state, the local view cells, which encode the robot's visual experience in the environment, and the experience map, which provides a semi-metric topological map that is used for navigation (Milford & Wyeth, 2009).

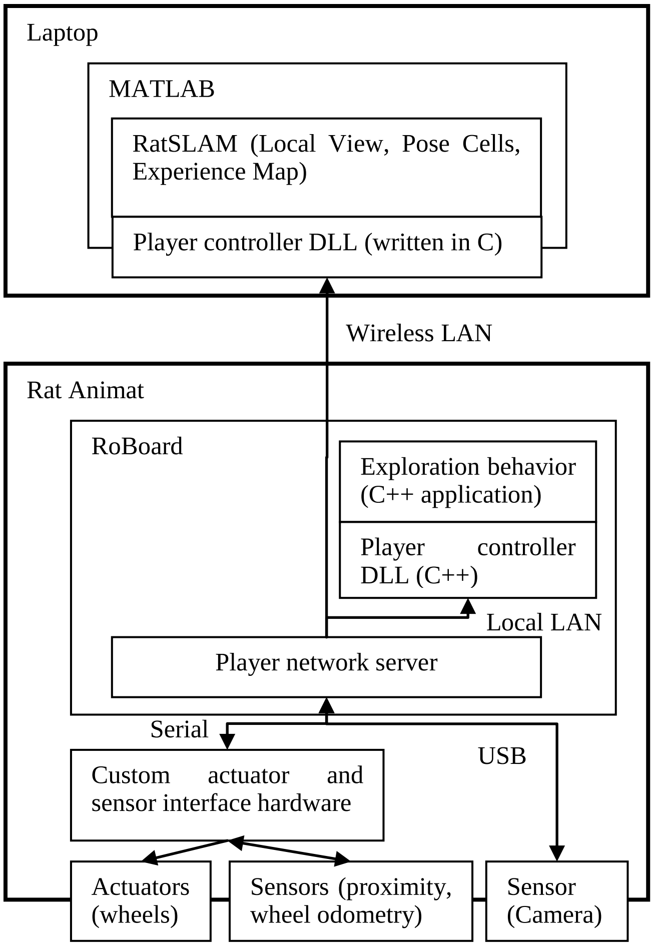

Fig. 3. This diagram shows the computational architecture demonstrating the possibilities using this rat animat and the *Player* framework. Arrows show the direction of main messages.

Experimental setup

The demonstration environment for the study was an approximately 1.5 x 1.5 meter figure of eight environment with walls of the same height as the robot, so the animat can see the rest of the lab for distal cues. The figure of eight has three loops (a large loop follows the outside wall of the arena, and two smaller loops follow the inner walls of the top and bottom halves of the figure of eight).

For this implementation of RatSLAM the view templates are histograms of column sums of the grayscale images given by the camera. New templates are compared to the stored templates using a correlation metric, with allowance for some rotation. The comparison determines whether the view is new or familiar: if new, a view template is created, and if familiar the best matching view template is determined. The bottom third of each image is typically the ground and has few distinct features appropriate for appearance based SLAM. Therefore, the robot only uses the top two thirds of the image for the view template histogram. Experiments were run for ten minutes with the robot navigating the three loops (one outer plus two inner) multiple times.

For this study the robot explored the environment using a center following behavior that attempted to maintain the same distance between the left and right wall based on readings from the IR proximity sensors. When the proximity to either wall becomes larger than a threshold then the robot would revert to either left or right wall following. These exploration behaviors were subsumed by obstacle avoidance based on the distance given by the IR sensors. For the majority of the experiment the robot travelled at 0.1 m/s. The exploration behavior ran on the robot connecting to *Player* via a local LAN connection receiving proximity distance and sending robot velocity commands at 4Hz

This study ran a MATLAB implementation of the RatSLAM navigation system on a laptop. The MATLAB version received odometry information (translational and rotational velocities) and camera images from the robot rat over wireless LAN. Fig 3 shows the experimental computational architecture. RatSLAM initially runs at 4Hz in real time but after the initial fast response, performance decreases due to the unbounded nature of the view templates and experience map in this lightweight MATLAB implementation. Because of the unbounded nature of the MATLAB version of RatSLAM, and to combine with overhead tracked images, the result figures were generated by logging the robot's camera images over Wireless LAN and then processing them offline.

Results

Fig 4 shows a comparison between the path given by the overhead tracking system, the integrated odometry path (given by the wheel velocities) and the final topological experience map given by RatSLAM. The experience map shows that the robot rat has approximately mapped the figure of eight environment. The paths show coherence within each loop, but the three loops don't completely overlap for three reasons. The first is that the centre, left and right wall following behaviors follow parallel but offset paths down the corridor resulting in different visual sequences. The second is that the centre following behavior has oscillations, particularly immediately after turning corners, which has an impact on the visual sequence. The third, and most important, is that traveling in both directions down a corridor results in different experience paths due to the forward facing camera not matching view templates. One of the primary causes is the camera's narrow field of view (approximately 50 degrees).

The experiment demonstrates the general nature of the RatSLAM system. Only minor adjustment of the visual processing algorithm was required from other applications of the RatSLAM system.

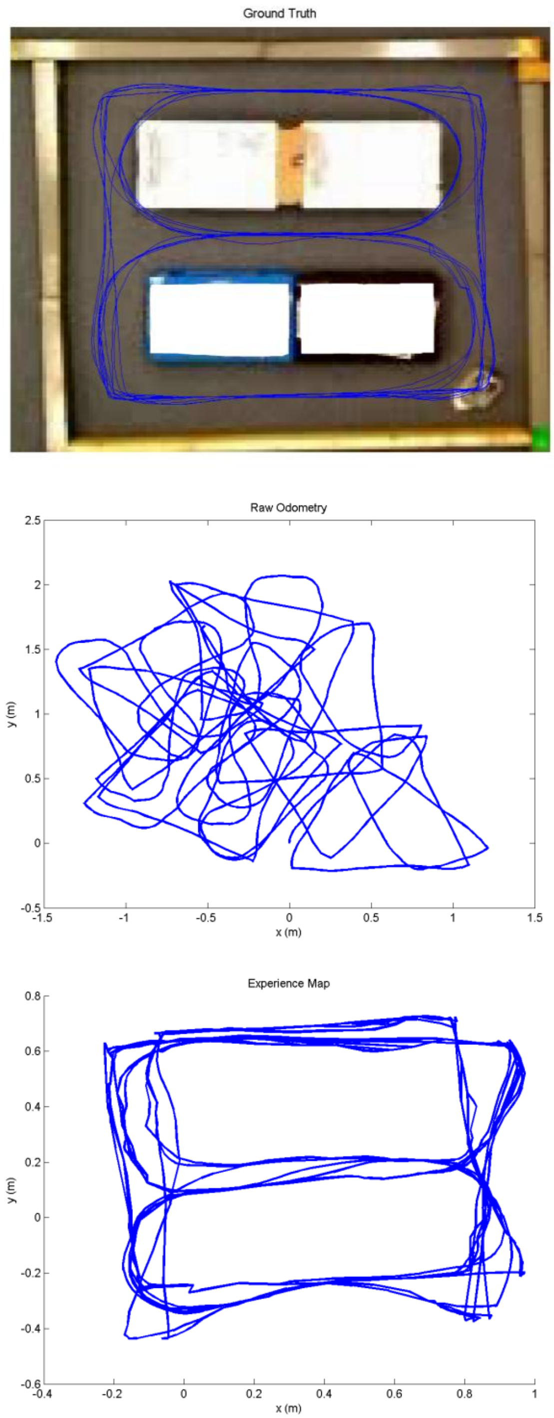

Fig. 4. (top) Path given by the overhead tracking system. The rat animat is in the bottom right corner. (middle) Raw odometry path given by integrating wheel velocities. (bottom) Semi-metric topological RatSLAM experience map that approximates the overhead tracked path.

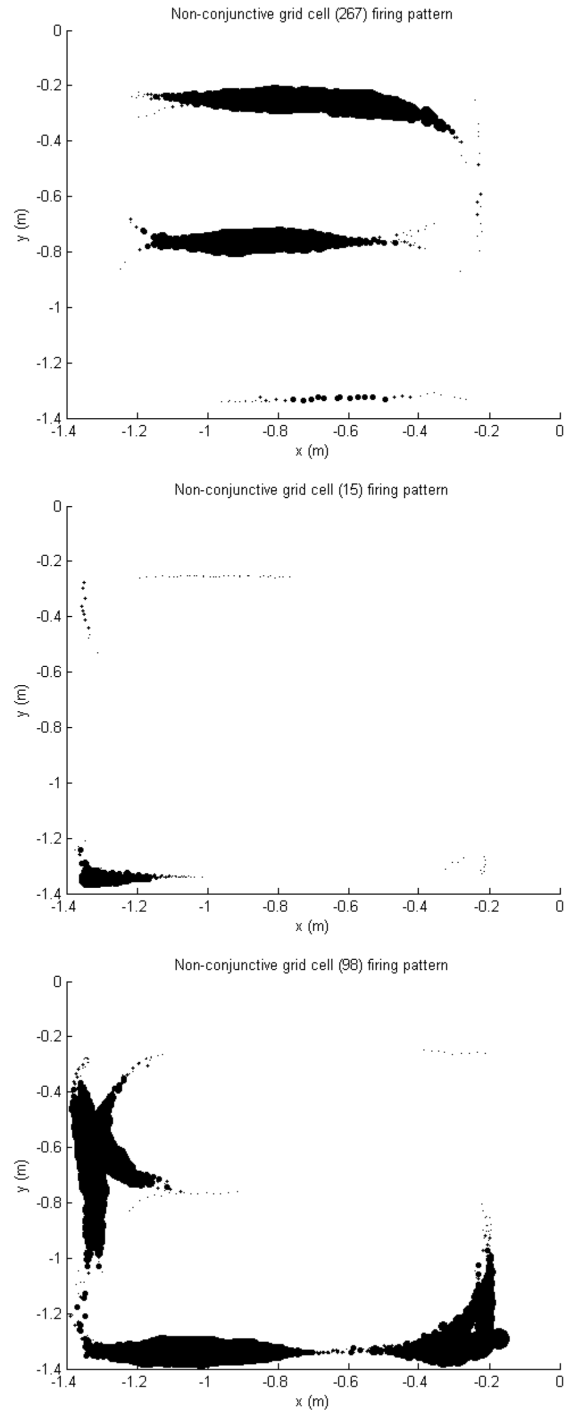

Fig. 5. Three ‘non-conjunctive grid cells’ as given by summing along the theta direction in the RatSLAM Pose Cell system. The size of the circle represents the level of activity. The figures show that the cells have different firing patterns. (top) The cell fires predominately in two corridors. (middle) The cell fires only in one corner of the environment. (bottom) The cell fires strongly in multiple locations in the environments.

Grid Cells

One of the original inspirations for the RatSLAM design was the rodent hippocampus. By plotting activity in an internal network of the distributed cognitive control architecture versus the position of the rat animat, it is possible to gain a firing field similar to 'non-conjunctive grid cells' prevalent in the rodent research field. These cells give a regular non-directional firing pattern. The equivalent of the 'non-conjunctive grid cells' is created by summing the activity of the RatSLAM pose cells along the θ' dimension, and plotting their average activity levels against the robot's overhead tracked location. Fig 5 shows the firing fields for three 'non-conjuctive grid cells'. The fields show that the cells fire in different locations and with different spatial properties. Some cells fire only in one part of the environment, whereas others fire across multiple sections. Note that the more typical regular firing pattern is not demonstrated in these plots because of the relatively small size of the environment compared to the pose cell network.

Discussion and Conclusions

This paper has described a new rodent animat platform similar in size to a large rat, which is capable of exploring and mapping an environment with multiple loops in real time. On board capabilities include visual, proximity, and odometry sensors, wheeled actuation and on-robot PC equivalent computation. The rat animat's distributed cognitive control architecture is not limited by on-robot computational resources as the *Player* framework allows for transparent communication over wireless LAN. The results demonstrate the rat animat's and *Player's* possibilities with using C/C++ and MATLAB in real time behaviors and SLAM distributed across the robot and other computers. This is significant as it will open up the platform to a broader range of researchers.

The paper began by highlighting the importance of embodiment with regard to the size of the real animal and the corresponding constraints on capabilities. This study has demonstrated that computational resources equivalent to a PC are now possible on a rat sized robot as well as real time connection to off-robot computation. The RatSLAM algorithm has shown itself to be remarkably generic, as it was ported from the pioneer robot to the robot rat with minimal adjustments. The order of magnitude change in camera height from the Pioneer robot to the rat animat does give a different perspective on the environment although this did not require any changes to the visual template matching technique. Changing from an omni-directional visual sensor to the forward facing small field of view sensor has had the most dramatic effect on the system performance as shown by the experience map connectivity. The experience map would benefit from using a visual sensor with a field of view similar to a real rat.

There are many avenues for future work. To allow longer experiments and users to interact with the robot via the web over the long term, the platform will need to be able to autonomously recharge with a docking station. Whiskers are important sensors for rodents that allow them to wall follow, detect obstacles and discriminate textures. Work has begun on developing a whisker system for this platform with these capabilities. On the neural controller side, the SLAM system needs to be integrated with a behavior system at a minimum capable of goal directed navigation and exploration. RatSLAM will also benefit from an improved visual perception system (hardware and neural controller) to improve performance. Other work will extend the behaviors for survival, social interactions and language games.

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References

Arleo, A., & Gerstner, W. (2000). Spatial cognition and neuro-mimetic navigation: a model of hippocampal place cell activity. *Biological Cybernetics, 83*, 287–299.

Barrera, A., & Weitzenfeld, A. (2008). Computational modeling of spatial cognition in rats and robotic experimentation: Goal-oriented navigation and place recognition in multiple directions. *Biomedical Robotics and Biomechatronics (BioRob2008)*, 789-794.

Beer, R. D. (2008). The Dynamics of Brain–Body–Environment Systems: A Status Report. In P. Calvo & T. Gomila (Eds.), *Handbook of cognitive science: an embodied approach*.

Beer, R. D., & Williams, P. L. (2009). Animals and Animats: Why Not Both Iguanas? *Adaptive Behavior, 17*(4).

Brooks, R. (1991). Intelligence without representation. *Artificial Intelligence*.

Burgess, N., Donnett, J. G., Jeffery, K. J., & O'Keefe, J. (1997). Robotic and neuronal simulation of the hippocampus and rat navigation. *Philosophical Transactions of the Royal Society of London B Biological Sciences, 352*, 1535-1543.

Doya, K., & Uchibe, E. (2005). The Cyber Rodent Project: Exploration of Adaptive Mechanisms for Self-Preservation and Self-Reproduction. *Adaptive Behaviour, 13*.

Fend, M. (2004). *The Artificial Mouse - A robot with whiskers and vision.* Paper presented at the 35th International Symposium on Robotics, Paris.

Fend, M., Bovet, S., & Pfeifer, R. (2006). On the influence of morphology of tactile sensors for behaviour and control. *Robotics and Autonomous System, 54*(8), 686-695.

Fox, C. W., Mitchinson, B., Pearson, M. J., Pipe, A. G., & Prescott, T. J. (2009). Contact type dependency of texture classification in a whiskered mobile robot. *Autonomous Robots, 26*, 223-239.

Gerkey, B. P., Vaughan, R. T., & Howard, A. (2003). *The Player/Stage Project: Tools for Multi-Robot and*

Distributed Sensor Systems. Paper presented at the International Conference on Advanced Robotics (ICAR 2003), Coimbra, Portugal.

Hafting, T., Fyhn, M., Molden, S., Moser, M., & Moser, E. I. (2005). Microstructure of a spatial map in the entorhinal cortex. *Nature, 436*, 801-806.

Ishii, H., Ogura, M., Kurisu, S., & Komura, A. (2006). *Experimental Study on Task Teaching to Real Rats Through Interaction with a Robotic Rat* Paper presented at the 9th International Conference on Simulation of Adaptive Behavior, SAB 2006.

Lacheze, L., Benosman, R., & Meyer, J.-A. (2008). *Integration of an Omnidirectional Visual System with the Control Architecture of Psikharpax* Paper presented at the 10th International Conference on Simulation of Adaptive Behavior, Osaka, Japan.

Mataric, M. J. (1991). Navigating with a rat brain: A neurobiologically-inspired model for robot spatial representation. *From Animals to Animats, MIT Press, Cambridge, MA*.

Meyera, J.-A., Guillota, A., Girarda, B., Khamassia, M., Pirimb, P., & Berthozc, A. (2005). The Psikharpax project: towards building an artificial rat. *Robotics and Autonomous System, 50*(4), 211-223.

Milford, M., & Wyeth, G. (2008). Mapping a Suburb with a Single Camera using a Biologically Inspired SLAM System. *IEEE Transactions of Robotics (Special Issue on Visual SLAM), 24*(5).

Milford, M., & Wyeth, G. (2009). Persistent Navigation and Mapping using a Biologically Inspired SLAM System. *International Journal of Robotics Research*.

O'Keefe, J., & Conway, D. H. (1978). Hippocampal place units in the freely moving rat: why they fire where they fire. *Experimental Brain Research, 31*(4), 573-590.

Patanè, F., Mattoli, V., Laschi, C., Mazzolai, B., Dario, P., Ishii, H., et al. (2007). *Biomechatronic Design and Development of a Legged Rat Robot*. Paper presented at the 2007 IEEE International Conference on Robotics and Biomimetics.

Pearson, M. J., Pipe, A. G., Melhuish, C., Mitchinson, B., & Prescott, T. J. (2007). Whiskerbot: A Robotic Active Touch System Modeled on the Rat Whisker Sensory System. *Adaptive Behavior, 15*(223).

Ranck Jr, J. B. (1984). Head-direction cells in the deep cell layers of dorsal presubiculum in freely moving rats. *Society Neuroscience Abstracts, 10*.

Samsonovich, A., & McNaughton, B. L. (1997). Path Integration and Cognitive Mapping in a Continuous Attractor Neural Network Model. *The Journal of Neuroscience, 17*(15), 5900-5920.

Stringer, S. M., Rolls, E. T., Trappenberg, T. P., & de Araujo, I. E. T. (2002). Self-organizing continuous attractor networks and path integration: two-dimensional models of place cells. *Network: Computation in Neural Systems, 13*(4), 429-446.

Stringer, S. M., Trappenberg, T. P., Rolls, E. T., & de Araujo, I. E. T. (2002). Self-organizing continuous attractor networks and path integration: one-dimensional models of head direction cells. *Network: Computation in Neural Systems, 13*(2), 217-242.

Takanishi, A., Aoki, T., Ito, M., Ohkawa, Y., & Yamaguchi, J. (1998). *Interaction between creature and robot: development of an experiment system for rat and rat robot interaction.* Paper presented at the IEEE Intelligent Robots and Systems.

Vaughan, R. (2008). Massively multi-robot simulation in stage. *Swarm Intelligence, 2*.

Webb, B. (2000). What does robotics offer animal behaviour? *Animal Behaviour, 60*, 545-558.

Webb, B. (2001). Can robots make good models of biological behaviour? *Behavioral and Brain Sciences, 24*(6), 1033-1050.