Simultaneous Localization and Active Phenomenon Inference (SLAPI)

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Abstract

We introduce the problem for a robot to localize itself, and, simultaneously, actively infer the existence and properties of *phenomena* present in its surrounding environment: the SLAPI problem. A phenomenon is a representation of an entity "as the robot experiences it" through interaction. The SLAPI problem relates to the SLAM problem but differs in that it does not aim at constructing a precise map of the environment, and it can apply to robots with coarse sensors. We demonstrate a SLAPI algorithm to control a robot equipped with omni-directional wheels, an echo-localization sensor, photosensitive sensors, and an inertial measurement unit, but no precise sensors like camera, lidar, or odometry. As the robot circles around an object, it constructs the phenomenon corresponding to this object under the form of the set of the spatially-localized control loops of interaction that the object affords to the robot. SLAPI algorithms could help design companion robots that mimic intrinsic motivation such as curiosity and playfulness. Further studies of the SLAPI problem could improve the scientific understanding of how cognitive beings construct knowledge about objects from sensorimotor experience of interaction.

Keywords: Constructivism; active inference; enaction; autonomous robotics; SLAM

1. Introduction

Hawkins et al. (2019) proposed the *thousand brain theory* to explain how the brain constructs knowledge of objects from sensorimotor experience using neuronal structures involving place cells distributed throughout the cortex. We situate this theory in the epistemological framework of developmental learning from sensorimotor experience, often attributed to Piaget. To test such theories, it is useful to design robots that autonomously learn from their experience of interacting with objects. Hawking specifically emphasizes the importance of spatial learning and conversion of spatial reference through displacement encoding.

In robotics, spatial learning has been formalized and studied since the 1990s under the name of the SLAM problem (Simultaneous Localization and Mapping): constructing and updating a map of an unknown environment while simultaneously keeping track of the robot's position within it (e.g., Taketomi et al., 2017). SLAM algorithms are tailored to the

available resources: odometric sensors, sensors of the environment, computational capacities, as well as the landmarks' properties, quantity, and dynamics, and the usage intended for the robot. When displacements are imprecise and odometric data is not available, and below a certain level of scarcity and noise in the sensory data relative to the environment's complexity, it becomes difficult to perform SLAM accurately (Gay et al., 2021).

The sensory system of humans and animals does not provide precise measures of distances and displacements. To investigate how an autonomous system equiped with coarse sensors can nonetheless perform sensorimotor spatial learning, we propose the SLAPI problem in robotics: Simultaneous Localization and Active Phenomenon Inference. In contrast with SLAM, SLAPI does not aim at constructing a map to use for navigation. Instead, it aims at organizing behavior spatially in the vicinity of objects to design robots that mimic intrinsic motivation such as playfulness and curiosity as they discover and interact with unknown objects (e.g., Oudeyer et al., 2007). Possible applications may not include delivery tasks but may include entertainment and games with lifelike companion robots, real of virtual.

SLAPI makes no assumption that landmarks can be directly distinctively identified through sensors. The robot must rather actively interact with objects, possibly from different angles and through different modalities of control loops, to categorize and recognize objects, and possibly use them as landmarks. We call this process *active phenomenon inference*, in line with the theory of active inference (e.g., Friston et al., 2021).

2. The representational status of sensory data

An autonomous agent faces the necessity to actively infer the presence and the properties of objects in its environment when such presence and properties are not directly registered in sensory data. This raises the question of the *representational status of sensory* data: is sensory data representational or not? This question has been discussed time and again at the philosophical level (e.g., Williford, 2013). Loosely, two hypotheses collide: the hypothesis that sensory data carry information about features of the world, versus the hypothesis that sensory data carry information about the agent's experience of interaction with the world. We refer to the former as the *representationalist hypothesis*, and to the latter as the *constructivist hypothesis* because it relates to Piaget's theory of construcitivist learning based on sensorimotor schemes (Guillermin and Georgeon, 2022).

SLAPI specifically helps investigate the constructivist hypothesis because the robot must probe the environment a little bit like a blind person who uses a cane to actively construct a mental representation of its surroundings. Probing experiences consist of control loops during which the robot interacts with the environment. They are triggered by an action selected by the robot and result in an outcome. The outcome is informative not of the object itself but of the possibility of interaction afforded by the object to the robot. Past probing experiences drive future behavior because they signal affordances for action. Figure 1 shows this cycle of interaction. The software selects an action associated with spatial information that specifies how the control loop should be enacted in the world. In return, the software receives an outcome associated with spatial information that describes how the control loop has been enacted depending on the actual nature and position of surrounding objects.
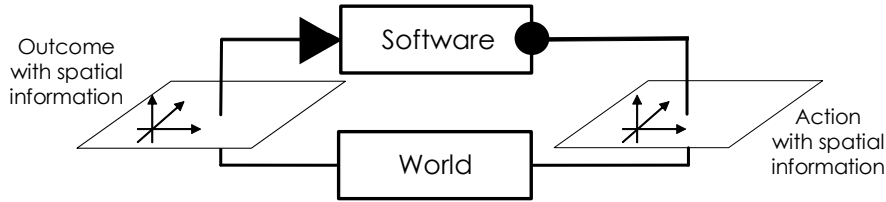
Figure 1: The interaction cycle. Black bullet: the cycle begins with the software selecting an action containing spatial information to enact in the world (right). Black arrowhead: the cycle ends with the software receiving the outcome containing spatial information (left).

Note that the constructivist hypothesis accepts that the outcome may sometimes register features of the environment but avoids "baking" this assumption in the algorithm *a priori*. Rudrauf et al. (2017) have also proposed an active inference model related to the constructivist hypothesis. They state that "All we need here is the idea that in one way or another the sensory organs provide an independent source of input and correction for the continually updated world model" (p. 19).

3. The experimental setup

We use the robot cat of brand Osoyoo[1], to which we added an inertial measurement unit (Figure 2). We use the omni-directional wheels only to move longitudinally or laterally (sweep). Section 4.1 will explain the primitive moves. Each primitive move induces an incertitude of displacement of about ±20% that we can't measure. The inertial measurement unit can only measure the yaw with the relatively good accuracy of ±1°. It also provides a compass with an accuracy of ±5°. We compute the robot's azimuth (angle from North) using both yaw integration (for precision) and compass (to correct drift). We then devise the absolute head direction knowing the head angle relative to the robot with good precision.

The robot can turn its head to perform echo localization in different directions. The distance measure has an accuracy of ±2mm but the detection cone spans 70°. We implemented two methods to estimate the direction of an object. Method 1 consists of scanning every 10° through the full range of head direction $[-\pi/2, \pi/2]$ and then computing the center of "strikes" of similar distances. Method 2 consists of turning the head by steps of 10° until finding a local minimum distance. We use Method 1 to find objects in the surrounding. We programmed the robot to keep its head aligned toward a *focus point* during its moves, and then to performs Method 2 to re-align its head towards the object.

We set up an environment with various objects that can be detected through echo-localization, and a black circle to delimit the robot's territory. With the inaccuracy of measures listed above, it is challenging to infer the position and shapes of objects. On the other hand, the robot has no target to reach. We only want it to explore its environment.

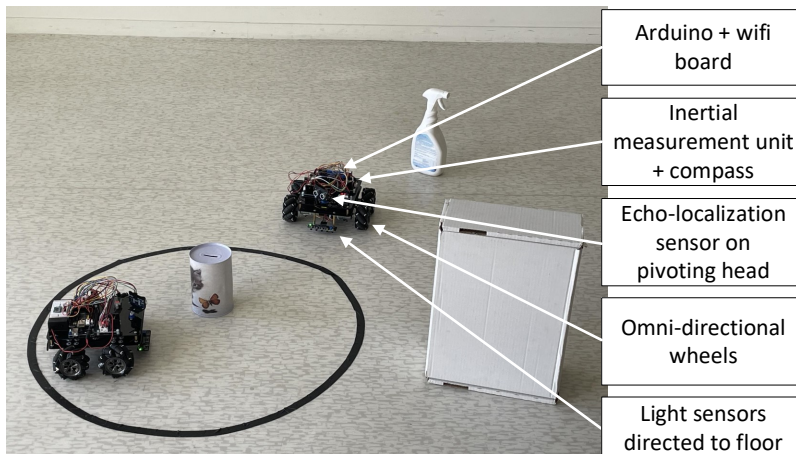1. https://osoyoo.com/2019/11/08/omni-direction-mecanum-wheel-robotic-kit-v1/

Figure 2: The experimental setup. Osoyoo robots, a black line on the floor, and various objects detectable through echo-localization. The omni-directional wheels allow the robot to translate laterally (sweep right or left).

4. The software architecture and algorithm

As a proof of concept to illustrate the SLAPI problem, we implemented the cognitive architecture depicted in Figure 3. This architecture is implemented on a remote PC and takes the place of the *Software* in Figure 1. The robot plus the environment take the place of the *World*.

The architecture follows a regular Model-View-Controller design pattern in which the *Memory* plays the role of the database, and the *Workspace* plays the role of the Model. As we will further develop, the *Memory* contains the egocentric memory and the allocentric memory which are displayed on screen via the *View Controllers* (Figure 3, right). The *Workspace* contains the *Decider* which implements the robot's policy, and the *Integrator* which infers the phenomena.

4.1. The control loops of interaction implemented in the robot

A C++ program on the robot's Arduino board handles the reception of the action from the PC through wifi, drives the control loop, and then sends the outcome back to the PC. Table 1 lists the supported actions and outcomes.

The reception of an action triggers the enaction of the corresponding control loop until its termination condition is satisfied. For example, the `Forward` action sets the robot in motion. It has three possible termination conditions: `Default`: time out of 1 second (approximately 20 cm traveled); `Line detection`: the floor sensor detects a line causing the robot to retreat back for a few centimeters; and `Impact`: the inertial measurement unit detects a strong deceleration indicating an impact with an object.

Besides the action code, the cognitive architecture sends two more values to the robot: the coordinates of the focus point if any, and an estimated speed. As introduced in Section 3,
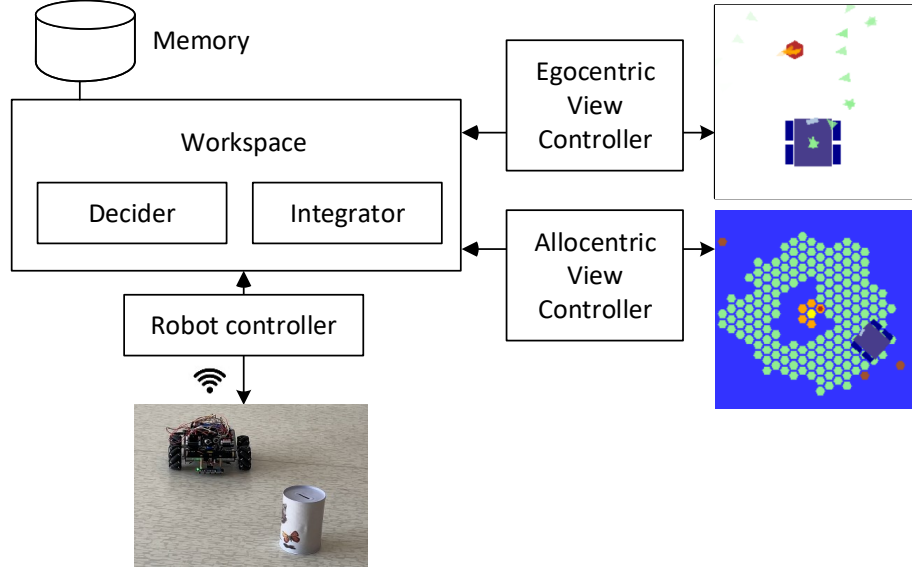
Figure 3: The software architecture implemented on a remote PC. Bottom: the robot interacting with a moneybox. It receives the action and sends back the outcome through wifi. Top-right: Egocentric memory display. Bottom-right: Allocentric memory display showing the constructed representation of the moneybox. Orange: echos, green: previous robot positions, red: focus point.

Table 1: Actions available to the robot and their possible outcomes

(*a*) Actions

Code	Description
Forward	During 1 sec.
Backward	or until
Sweep left	impact or line
Sweep right	detection
Turn left	by $\pi/4$
Turn right	by $-\pi/4$
Head scan	$-\pi/2$ to $\pi/2$

(*b*) Outcomes

Code	Description
Line left	Floor sensors
Line front	cross luminosity
Line right	threshold
Impact	Violent deceleration
Echo lost focus	No echo where expected
Echo left	
Echo right	
Echo far left	Direction and
Echo far right	range of the
Echo far front	nearest echo
Echo close front	
Default	No line, no echo

the robot uses them to keep its head aligned towards objects over successive moves. This behavior gives the human observer the impression that the robot keeps its attention on a particular object, making it look more alive.

The robot also returns additional information to the cognitive architecture: yaw, azimuth (angle relative to the north), and duration of the various phases of the control loop. The cognitive architecture uses this information to update the spatial memory based on the robot's displacement. The termination phase of the control loop aligns the robot's head towards the nearest echo. The robot then also returns the nearest echo measure along with the head direction. The cognitive architecture uses this information to mark the position of the echo in spatial memory. This will be used to infer the presence of an object when multiple echos are localized in the same area. Table 2 summarizes the data exchanged between the PC and the robot.

Table 2: Dialogue between the PC and the robot through wifi

PC to Robot	Action code, focus coordinates (x, y), estimated speed (x, y)
Robot to PC	Outcome code, echo distance, head direction, yaw, azimuth, duration

4.2. Egocentric memory

The egocentric memory is a short-term spatial memory of the experiences of interaction in the surrounding of the robot. It is inspired by the brain's egocentric cells located in the superior colliculus (Grieves and Jeffery, 2017).

Technically, it stores the robot's *experiences* in a coordinate system centered on the robot. An experience is a data structure that contains the action, the outcome, the position in space relative to the robot, and the timestamp. Our implementation initializes the position from a hard-coded model of the robot: line-detection experiences are placed at the position of the floor sensors; echo experiences are placed at the estimated origin of the echo using head direction and measure of echo distance. Additionally, echo experiences also store the direction of the sensor needed by the phenomenon inference function. When the robot moves, the positions of experiences are then moved opposite by the robot's estimated displacement (Figure 3, top right). Due to the imprecision listed in Section 3, errors in the estimation of the robot's position accumulate causing a drift in egocentric memory. Our implementation removes the experiments older than 10 interaction cycles from the egocentric memory display because they are unreliable.

4.3. Allocentric memory

The allocentric memory is inspired by *grid cells* in the entorhinal cortex (Grieves and Jeffery, 2017), and reproduces their hexagonal structure. Technically, it stores a set of *affordances* that represent the possibilities of interaction afforded by the environment to the robot. An affordance is an experience associated with its position in allocentric reference (Figure 4).

Converting from egocentric to allocentric reference requires establishing an origin point from which path integration can be performed. If this origin point is immobile and recog-

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nizable later, it can be used to correct the robot's position and avoid infinite accumulation of position errors. Fortunately, in our case, we can use the position of the echo associated with the absolute head direction to recognize the origin point when the robot has performed a complete tour around the object. This solution works if the object is convex, as long as the robot does not mistake objects.
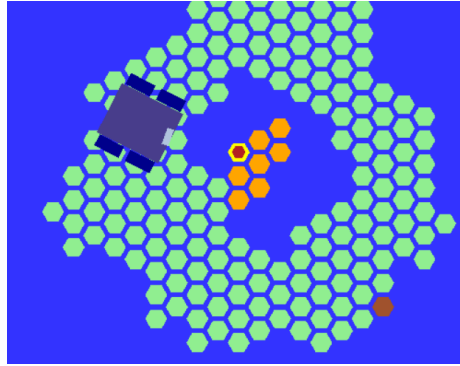

Figure 4: Example allocentric memory after circling around an oblong object. Green: cells previously traversed by the robot. Orange: echos localized with Method 1. Yellow: origin of the phenomenon. Small red hexagon: current focus point. Brown: echos localized with method 2 (in this example coming from another object).

4.4. The phenomenon integrator

The phenomenon integrator constructs a data structure that represents an object in term of affordances. We call this data structure a *phenomenon* in compliance with the common sense usage of this term: the perception by a cognitive being of "something" in the environment. (Thórisson, 2021, p. 8) provides a more technical definition that also matches our usage: "any useful grouping of a subset of spatio-temporal patterns experienced by an agent in an environment". Notably, these action-related representations of objects also resemble *action codes* that have been found in parietal regions of the cerebral cortex of humans and other primates (Chao and Martin, 2000; Colby and Goldberg, 1999; Schubotz et al., 2014). Like our affordances, action codes are linked to memory traces of previous actions involving the object.

Our phenomenon data structure contains a set of affordances and a decimal *confidence coefficient* in the range $[0, 1]$. We implemented Algorithm 1 to address the difficulty of localizing affordances relative to an initially unknown phenomenon while the robot's estimated position is prone to error.

Algorithm 1 takes a newly found affordance object in input, and returns the distance vector by which the robot's position must be corrected. Lines L1 and L2 compare the position vector of the new affordance with the position vector of the nearest affordance already attached to this phenomenon. L3: if the difference is below *MAX_DISTANCE*, the new affordance is considered belonging to this phenomenon. L4: the method *similar_to()*

compares the new affordance with the *origin affordance* (the first affordance attached to this phenomenon) on the basis of their positions and their absolute head directions. L5: the method *increase_confidence()* keeps track of the number of tours the robot has made around the object. When a new affordance is found similar to the *origin affordance* after a new tour, it increases the phenomenon's *confidence* coefficient. L6: the *position_correction* vector is computed to reposition the robot at the origin position given by the *origin affordance*. L8: when the new affordance is not similar to the *origin affordance*, the length of the *position_correction* vector is made proportional to the *confidence* coefficient. L10: the position of the new affordance is corrected by the *position_correction* vector. This means that, when the confidence in the phenomenon is close to zero at the beginning, the robot rests on its estimated position to roughly estimate the phenomenon's shape. When the confidence in the phenomenon becomes close to one after several tours, the robot ceases updating the phenomenon's shape and rather corrects its own position relative to the phenomenon. L11: *phenomenon.prune()* removes old affordances near the new one that have become irrelevant. L12: *phenomenon.append()* attaches the new affordance to the phenomenon. L14: returns the *position_correction* vector to correct the robot's position.

Algorithm 1: Phenomenon.update(affordance)

$nearest\_affordance \leftarrow phenomenon.find\_nearest(affordance)$;
$delta \leftarrow nearest\_affordance.position - affordance.position$;
if $delta < MAX\_DISTANCE$ **then**
    if $affordance.similar\_to(origin\_affordance)$ **then**
        $phenomenon.increase\_confidence()$;
        $position\_correction = origin\_affordance.position - affordance.position$;
    else
        $position\_correction = phenomenon.confidence * delta$;
    end
    $affordance.position \leftarrow affordance.position + position\_correction$;
    $phenomenon.prune(affordance)$;
    $phenomenon.append(affordance)$;
end
return $position\_correction$

Figure 5 shows two example phenomena learned by the robot with this algorithm. It shows that the object's shapes inferred by the robot, while imprecise, allow discriminating between different objects.

4.5. The decider

The Decider implements the policy that selects the robot's actions. For our proof of concept, we used decision mechanism inspired by our previous work (Georgeon et al., 2013; Robertson and Laddaga, 2009). It stores a *list of behaviors* in the form of *sequences of experiences* that the robot can enact. After each interaction cycle, the Decider activates the sequences in this list whose beginning sub-sequence matches experiences present in memory. The activated sequences then propose their ending sub-sequences for further enaction with a
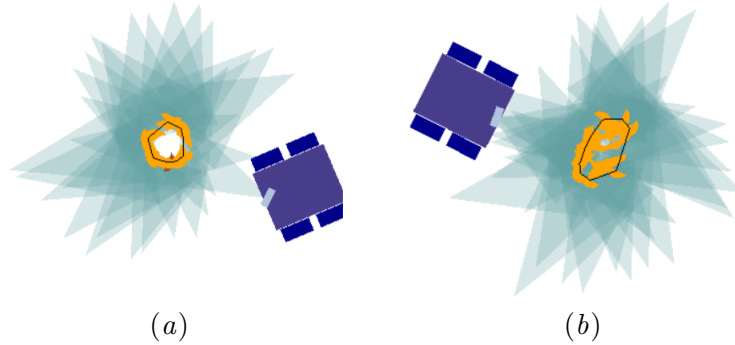
(a) (b)

Figure 5: Example phenomena a) learned from the moneybox shown in Figure 3, b) from two moneyboxes next to each other. Each affordance is represented by a gray triangle (cone of echo-localization) and an orange half-circle (estimated position of echo). Black line: the object's outline estimated by the robot.

weight. Finally the Decider selects the sub-sequence that is proposed with the highest weight. We have initialized the list of behaviors with predefined behavioral patterns that give the robot a tendency to circle around objects when it detects them.

With this policy, the robot wanders randomly until it detects an object nearby, and then it circles around this object until the experimenter removes the object. This is sufficient for our demonstration. In future studies, we will implement more complex information-seeking policies, possibly inspired by a rich recent literature on this topic (e.g. Gottlieb and Oudeyer, 2018).

5. More demonstrations

Videos of example runs are available on Titouan Knockaert's and Olivier Georgeon's youtube channels. Knockaert (2022) demonstrates the robot circling around an object while constructing the egocentric and allocentric maps. Georgeon (2021) shows the robot interacting with black lines and the user. Now we are working on demonstrating the learning of phenomena from different sensory modalities. It is worth noting that many human observers attribute the intention of the robot to carefully observe the object due to the fact that it keeps its head pointing to the object.

6. Conclusion

This paper presents the SLAPI problem: the problem for an autonomous artificial agent to construct knowledge about entities in its environment from sensorimotor experience of interaction. This problem is particularly salient when the agent has rudimentary sensors that provide poor information about the features of the environment. In this case, to be informative, sensory data should rather be considered as *outcome* of a control loop than *percepts*.

On the contrary, when the agent has rich sensors that allow the identification of features of the world, it is tempting for the developer of the agent's software to consider that sensory data carries representational information about the world. Philosophy of mind, however, provides theoretical arguments against this representationalist hypothesis. These arguments go back to Kant, who claimed that the world "in itself" is unknowable, and relate to Piaget's developmental psychology and theory of enaction (e.g., Froese and Ziemke, 2009). If we trust these arguments, we can expect SLAPI algorithms to also bring value to agents that have rich sensors. They could endow such agents with more autonomy in the way they construct their own knowledge of the world, and keep this knowledge grounded in their individual experience of interaction.

We reported our implementation and experiment as an initial example to illustrate the SLAPI problem, in the hope that it provides clarification on how SLAM techniques can be used to study autonomous constructivist learning. We hope that future models will address more complex problems of phenomenal inference such as recognition of similarities and differences between types of phenomena and composition of parts of phenomena, as called for by Hawkins et al. (2019). A more precise evaluation of the performance of the integrator's mechanism may also tell us whether it holds further similarities with observed neuronal representations of action in the brain. More broadly, such models can improve our understanding of how animals construct knowledge of objects through enaction.

Acknowledgments

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