Noise and the Common Sense Informatic Situation for a Mobile Robot

Murray Shanahan

Department of Computer Science,
Queen Mary and Westfield College,
Mile End Road,
London E1 4NS,
England.
mps@dcs.qmw.ac.uk

Abstract

Any model of the world a robot constructs on the basis of its sensor data is necessarily both incomplete, due to the robot's limited window on the world, and uncertain, due to sensor and motor noise. This paper supplies a logical account of sensor data assimilation in which such models are constructed through an abductive process which hypothesises the existence, locations, and shapes of objects. Noise is treated as a kind of non-determinism, and is dealt with by a consistency-based form of abduction.

Introduction

The aim of Cognitive Robotics is to design and build mobile robots based on the idea of logical representation [Lespérance, *et al.*, 1994]. By reinstating the ideals of the Shakey project [Nilsson, 1984], Cognitive Robotics has reinvigorated a research programme that has been largely dormant for the past twenty years.

This has been made possible by recent advances in the field of common sense reasoning: formalisms now exist for reasoning about action which incorporate robust solutions to the frame problem, and which can represent a wide variety of phenomena, including concurrent action, non-deterministic action, and continuous change.

The Cognitive Robotics approach is in marked contrast to that of Brooks and his followers. According to Brooks, work in the style of Shakey is flawed because,

> it [relies] on the assumption that a complete world model [can] be built internally and then manipulated.
>
> [Brooks, 1991a]

A complete model of the world is hard for a robot to construct because, as Brooks points out,

> the data delivered by sensors are not direct descriptions of the world as objects and their relationships [and] commands to actuators have very uncertain effects.
>
> [Brooks, 1991b]

This sort of incompleteness and uncertainty is a feature of what McCarthy [1989] calls the *common sense informatic situation*, and is dealt with extremely well by predicate logic. This paper supplies a logical account of the common sense informatic situation for a small mobile robot with very poor sensors, and thereby defends the Cognitive Robotics approach from arguments along the lines of the one advanced above.

The paper is organised as follows. Section 1 presents a generic formalism for reasoning about action and space. Section 2 applies this formalism to the mobile robot under consideration, and presents an abductive characterisation of sensor data assimilation. A more detailed presentation of the material in these two sections is to be found in [Shanahan, 1996b]. The next two sections focus on the issue of noise. Section 3 shows how noise can be considered as a form of non-determinism, and Section 4 shows how the abductive characterisation of Section 2 can be modified to handle this non-determinism.

1 Representing Action and Space

The proposed framework is the product of three steps.

1. Develop a formalism for representing action, continuous change, space and shape.
2. Using this formalism, construct a theory of the robot's interaction with the world.
3. Consider the process of sensor data assimilation as a form of abduction, following [Shanahan, 1989].

This section concerns the first of these steps. For more details, see [Shanahan, 1996b]. To begin with, we have a formalism for reasoning about action and continuous change, based on the circumscriptive event calculus of [Shanahan, 1995b]. A many sorted language is assumed, with variables for *fluents*, *actions* (events), and *time points*. We have the following axioms, whose conjunction will be denoted CEC. Their main purpose is to constrain the predicate HoldsAt. HoldsAt(f,t) represents that fluent f holds at time t.

$$\text{HoldsAt}(f,t) \leftarrow \text{Initially}(f) \wedge \neg \text{Clipped}(0,f,t) \qquad \text{(EC1)}$$

$$\text{HoldsAt}(f,t2) \leftarrow \text{Happens}(a,t1) \wedge \text{Initiates}(a,f,t1) \wedge t1 < t2 \wedge \neg \text{Clipped}(t1,f,t2) \qquad \text{(EC2)}$$

$$\neg \text{HoldsAt}(f,t2) \leftarrow \quad \text{(EC3)}$$
$$\text{Happens}(a,t1) \wedge \text{Terminates}(a,f,t1) \wedge t1 < t2 \wedge \neg \text{Declipped}(t1,f,t2)$$

$$\text{Clipped}(t1,f,t2) \leftrightarrow \quad \text{(EC4)}$$
$$\exists a,t\, [\text{Happens}(a,t) \wedge [\text{Terminates}(a,f,t) \vee \text{Releases}(a,f,t)] \wedge t1 < t \wedge t < t2]$$

$$\text{Declipped}(t1,f,t2) \leftrightarrow \quad \text{(EC5)}$$
$$\exists a,t\, [\text{Happens}(a,t) \wedge [\text{Initiates}(a,f,t) \vee \text{Releases}(a,f,t)] \wedge t1 < t \wedge t < t2]$$

$$\text{HoldsAt}(f2,t2) \leftarrow \quad \text{(EC6)}$$
$$\text{Happens}(a,t1) \wedge \text{Initiates}(a,f1,t1) \wedge t1 < t2 \wedge t2 = t1 + d \wedge \text{Trajectory}(f1,t1,f2,d) \wedge \neg \text{Clipped}(t1,f1,t2)$$

A particular domain is described in terms of Initiates, Terminates, Releases, and Trajectory formulae. Initiates(a,f,t) represents that fluent f starts to hold after action a at time t. Conversely, Terminates(a,f,t) represents that f starts to not hold after action a at t. Releases(a,f,t) represents that fluent f is no longer subject to default persistence after action a at t. The Trajectory predicate is used to capture continuous change. Trajectory(f1,t,f2,d) represents that f2 holds at time t+d if f1 starts to hold at time t.

A particular narrative of events is represented in terms of Happens and Initially formulae. The formula Initially(f) represents that fluent f holds at time 0. Happens(a,t) represents that action a occurs at time t.

In rough terms, if E is a domain description and N is a narrative description, then the frame problem is overcome by considering,

$$\text{CIRC}[N ; \text{Happens}] \wedge \text{CIRC}[E ; \text{Initiates, Terminates, Releases}] \wedge \text{CEC}.$$

However, care must be taken when domain constraints and triggered events are included. The former must be conjoined to CEC, while the latter are conjoined to N. A detailed account of this solution is to be found in [Shanahan, 1996a, Chapter 16].

To construct a theory of the robot's interaction with the world, a means of representing space and shape is required. Space is assumed to be $\mathbb{R}^2$. Objects occupy *regions*, which are open, path-connected subsets of $\mathbb{R}^2$. The following axioms will be required, defining the functions Disc, Distance, Bearing, and Line. The intended meaning of these functions should be obvious.

$$p \in \text{Disc}(z) \leftrightarrow \text{Distance}(p,\langle 0,0\rangle) < z \quad \text{(Sp1)}$$

$$\text{Distance}(\langle x1,y1\rangle,\langle x2,y2\rangle) = \sqrt{(x1-x2)^2 + (y1-y2)^2} \quad \text{(Sp2)}$$

$$\text{Bearing}(\langle x1,y1\rangle,\langle x2,y2\rangle) = r \leftarrow \quad \text{(Sp3)}$$
$$z = \text{Distance}(\langle x1,y1\rangle,\langle x2,y2\rangle) \wedge z \neq 0 \wedge \text{Sin}(r) = \frac{x2-x1}{z} \wedge \text{Cos}(r) = \frac{y2-y1}{z}$$

$$p \in \text{Line}(p1,p2) \leftrightarrow \quad \text{(Sp4)}$$
$$\text{Bearing}(p1,p) = \text{Bearing}(p1,p2) \wedge \text{Distance}(p1,p) \leq \text{Distance}(p1,p2)$$

Spatial occupancy is represented by the fluent Occupies. The term Occupies(w,g) represents that region g is the smallest region which covers all the space occupied by object w. Objects cannot overlap, and can only occupy one region at a time.

$$[\text{HoldsAt}(\text{Occupies}(w,g1),t) \wedge \text{HoldsAt}(\text{Occupies}(w,g2),t)] \rightarrow g1 = g2 \quad \text{(Sp5)}$$

$$\text{HoldsAt}(\text{Occupies}(w1,g1),t) \wedge \text{HoldsAt}(\text{Occupies}(w2,g2),t) \wedge w1 \neq w2 \rightarrow \neg \exists p\, [p \in g1 \wedge p \in g2] \quad \text{(Sp6)}$$

The Displace function will be used to capture the robot's continuous motion through space. Displace(g,⟨x,y⟩) denotes the region obtained by displacing g by x units east and y units north.

$$\langle x1,y1\rangle \in \text{Displace}(g,\langle x2,y2\rangle) \leftrightarrow \langle x1-x2,y1-y2\rangle \in g \quad \text{(Sp7)}$$

For reasons set out in [Shanahan, 1995a], a means of default reasoning about spatial occupancy is required. This is done by minimising the predicate AbSpace in the presence of the following axiom.

$$\text{AbSpace}(w) \leftarrow \text{Initially}(\text{Occupies}(w,g)) \quad \text{(Sp8)}$$

Let O denote the conjunction of (Sp1) to (Sp8). As we'll see in the next section, O is included in a separate circumscription describing the initial situation, in which AbSpace is minimised. In the present context, this is a description of the initial locations and shapes of objects, in other words a map.

2 The Robot's Relationship to the World

Shortly, the abductive process whereby maps are constructed out of the robot's sensor data will be defined. First, a theory has to be constructed which captures the robot's relationship to the world: the effects of its actions on the world, and the effect of the world on its sensors. This theory is constructed using the formalism of the previous section.

The robot under consideration is based on the Rug Warrior described by Jones and Flynn [1993]. This is a circular robot with two drive wheels. The three actions it can perform are to rotate by a given number of degrees, to start moving forwards, and to stop. It has two forward bump switches, which can detect collisions.

First we have a pair of uniqueness-of-names axioms for the three fluents Occupies, Facing and Moving, and for the robot-performed actions Rotate, Go and Stop, and the triggered events Bump, Switch1 and Switch2.

$$\text{UNA}[\text{Occupies, Facing, Moving, Blocked, Touching}] \quad \text{(B1)}$$

$$\text{UNA}[\text{Rotate, Go, Stop, Bump, Switch1, Switch2}] \quad \text{(B2)}$$

Next we have a Trajectory formula which describes the continuous variation in the Occupies fluent as the robot moves through space, and a collection of domain constraints. The robot moves one unit of distance in one unit of time. Blocked(w1,w2,r) means that object w1 cannot move in direction r because it is obstructed by object w2. Touching(w1,w2,p) means that objects w1 and w2 are touching at point p.

$Trajectory(Moving,t,Occupies(Robot,g2),d) \leftarrow$ (B3)
$\quad HoldsAt(Occupies(Robot,g1),t) \wedge$
$\quad\quad HoldsAt(Facing(r),t) \wedge$
$\quad\quad\quad g2 = Displace(g1,\langle d.Sin(r),d.Cos(r)\rangle)$

$HoldsAt(Facing(r1),t) \wedge$ (B4)
$\quad HoldsAt(Facing(r2),t) \rightarrow r1=r2$

$HoldsAt(Blocked(w1,w2,r),t) \leftrightarrow$ (B5)
$\quad \exists\, g1,g2\ [HoldsAt(Occupies(w1,g1),t) \wedge$
$\quad\quad HoldsAt(Occupies(w2,g2),t) \wedge$
$\quad\quad\quad w1 \neq w2 \wedge \exists\, z1\ [z1 > 0 \wedge \forall\, z2\ [z2 \leq z1 \rightarrow$
$\quad\quad\quad\quad \exists\, p\ [p \in g2 \wedge$
$\quad\quad\quad\quad\quad p \in Displace(g1,\langle z2.Sin(r),z2.Cos(r)\rangle)]]]]$

$HoldsAt(Touching(w1,w2,p),t) \leftrightarrow$ (B6)
$\quad HoldsAt(Occupies(w1,g1),t) \wedge$
$\quad\quad HoldsAt(Occupies(w2,g2),t) \wedge w1 \neq w2 \wedge$
$\quad\quad\quad \exists\, p1, p2\ [p \in Line(p1,p2) \wedge p \neq p1 \wedge p \neq p2 \wedge$
$\quad\quad\quad\quad \forall\, p3\ [[p3 \in Line(p1,p) \wedge p3 \neq p] \rightarrow$
$\quad\quad\quad\quad\quad p3 \in g1] \wedge$
$\quad\quad\quad\quad\quad\quad \forall\, p3\ [[p3 \in Line(p,p2) \wedge p3 \neq p] \rightarrow$
$\quad\quad\quad\quad\quad\quad\quad p3 \in g2]]$

Let B denote the conjunction of CEC with Axioms (B1) to (B6). Next we have a collection of Initiates, Terminates and Releases formulae.

$Initiates(Rotate(r1),Facing(r1+r2),t) \leftarrow$ (E1)
$\quad HoldsAt(Facing(r2),t)$

$Releases(Rotate(r1),Facing(r2),t) \leftarrow$ (E2)
$\quad HoldsAt(Facing(r2),t) \wedge r1 \neq 0$

$Initiates(Go,Moving,t)$ (E3)

$Releases(Go,Occupies(Robot,g),t)$ (E4)

$Terminates(a,Moving,t) \leftarrow$ (E5)
$\quad a = Stop \vee a = Bump \vee a = Rotate(r)$

$Initiates(a,Occupies(Robot,g),t) \leftarrow$ (E6)
$\quad [a = Stop \vee a = Bump] \wedge$
$\quad\quad HoldsAt(Occupies(Robot,g),t)$

Let E denote the conjunction of Axioms (E1) to (E6). The final component of the theory describes the conditions under which Bump, Switch1 and Switch2 events are triggered.

$Happens(Bump,t) \leftarrow$ (H1)
$\quad [HoldsAt(Moving,t) \vee Happens(Go,t)] \wedge$
$\quad\quad HoldsAt(Facing(r),t) \wedge$
$\quad\quad\quad HoldsAt(Blocked(Robot,w,r),t)$

$Happens(Switch1,t) \leftarrow$ (H2)
$\quad Happens(Bump,t) \wedge HoldsAt(Facing(r),t) \wedge$
$\quad\quad HoldsAt(Occupies(Robot,Displace(Disc(z),p1)),t) \wedge$
$\quad\quad\quad HoldsAt(Touching(Robot,w,p2),t) \wedge$
$\quad\quad\quad\quad r-90 \leq Bearing(p1,p2) < r+12$

$Happens(Switch2,t) \leftarrow$ (H3)
$\quad Happens(Bump,t) \wedge HoldsAt(Facing(r),t) \wedge$
$\quad\quad HoldsAt(Occupies(Robot,Displace(Disc(z),p1)),t) \wedge$
$\quad\quad\quad HoldsAt(Touching(Robot,w,p2),t) \wedge$
$\quad\quad\quad\quad r-12 \leq Bearing(p1,p2) < r+90$

We're now in a position to supply an abductive characterisation of the task of sensor data assimilation, where the robot's sensor data is a stream of Switch1 and Switch2 events. First we have a definition which permits the exclusion of certain anomalous explanations, by ensuring that *only* the sensor data the robot actually receives is abductively explained.

Definition 2.1.

$$COMP[\Psi] \equiv_{def} [Happens(a,t) \wedge [a = Switch1 \vee a = Switch2]] \rightarrow \bigvee_{\langle\alpha,\tau\rangle \in \Gamma} [a = \alpha \wedge t = \tau]$$

where $\Gamma = \{\langle\alpha,\tau\rangle \mid Happens(\alpha,\tau) \in \Psi\}$. □

Sensor data assimilation is the task of finding explanations of the sensor data in terms of hypothesised objects. Given an Initially formula M1 describing the initial location of the robot, a collection N2 of Happens formulae describing the robot's actions, and a collection Ψ of Happens formulae describing the sensor data received by the robot, we're interested in finding conjunctions M2 of formulae in which each conjunct has the form,

$$\exists\, g\ [Initially(Occupies(\omega,g)) \wedge \forall\, p\ [p \in g \leftrightarrow \Pi]]$$

where ω is an object constant and Π is any formula in which p is free, such that $O \wedge M1 \wedge M2$ is consistent and,

$CIRC[O \wedge M1 \wedge M2\ ;\ AbSpace\ ;\ Initially] \wedge$
$\quad CIRC[N1 \wedge N2\ ;\ Happens] \wedge$
$\quad\quad CIRC[E\ ;\ Initiates, Terminates, Releases] \wedge B \models$
$\quad\quad\quad \Psi \wedge COMP[\Psi].$

This definition is very liberal, and the full paper utilises a *boundary-based* representation of shape to render the space of possible explanations more manageable (see [Davis, 1990, Chapter 6]).

3 Noise as Non-Determinism

The hallmark of the common sense informatic situation for a mobile robot is incomplete and uncertain knowledge of a world of spatio-temporally located objects. Incompleteness is a consequence of the robot's limited window on the world, and uncertainty results from noise in its sensors and actuators. This section deals with noise.

Both noisy sensors and noisy actuators can be captured using non-determinism. (An alternative is to use probability [Bacchus, *et al.*, 1995]). Here we'll only look at the uncertainty in the robot's location that results from its noisy motors. The robot's motors are "noisy" for various reasons. For example, the two wheels might rotate at slightly different speeds when the robot is trying to travel in a straight line, or the robot might be moving on a slope or a slippery surface.

Motor noise of this kind can be captured using a non-deterministic Trajectory formula, such as the following replacement for Axiom (B3).[1] Note that, while objects

[1] The Rotate action could also have been made non-deterministic.

occupy open subsets of $\mathbb{R}^2$, regions of uncertainty are closed.

$$\begin{aligned}&\exists\, p\, [\text{Trajectory}(\text{Moving},t,\\&\quad \text{Occupies}(\text{Robot},\text{Displace}(g,p)),d) \wedge \\&\quad\quad \text{Distance}(p,\langle d.\text{Sin}(r),d.\text{Cos}(r)\rangle) \leq d.\varepsilon] \leftarrow\\&\quad\quad\quad \text{HoldsAt}(\text{Occupies}(\text{Robot},g),t) \wedge\\&\quad\quad\quad\quad \text{HoldsAt}(\text{Facing}(r),t)\end{aligned} \quad \text{(B7)}$$

In effect, Axiom (B7) constrains the robot's location to be within an ever-expanding *circle of uncertainty* centred on the location it would be in if its motors weren't noisy. The constant ε determines the rate at which this circle grows. Axiom (B8) below ensures that there are no discontinuities in the robot's trajectory. Without this axiom the robot would be able to leap over any obstacle which didn't completely cover the circle of uncertainty for its location. The term Abs(d) denotes the absolute value of d.

$$\begin{aligned}&\text{Trajectory}(f,t,\text{Occupies}(x,\text{Displace}(g,p1)),d1) \rightarrow\\&\quad \forall\, z\, [z > 0 \rightarrow\\&\quad\quad \exists\, d\, \forall\, d2,p2\ \ [[d2 > 0 \wedge \text{Abs}(d2-d1) < d \wedge\\&\quad\quad\quad \text{Trajectory}(f,t,\text{Occupies}(x,\text{Displace}(g,p2)),d2)] \rightarrow\\&\quad\quad\quad\quad \text{Distance}(p1,p2) < z]]\end{aligned} \quad \text{(B8)}$$

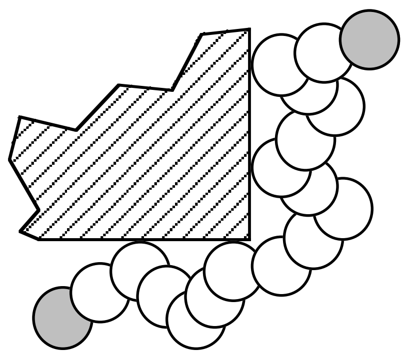

Figure 1: The Robot Explores a Corner

Figure 1 shows the robot exploring the corner of an obstacle. Figure 2 shows the evolution of the corresponding circle of uncertainty, highlighting the points where the robot changes direction.

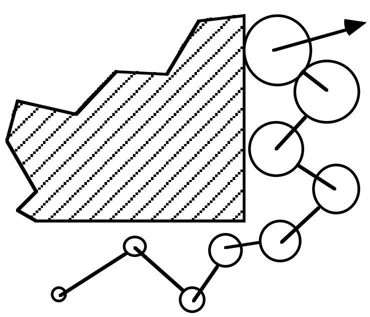

Figure 2:
The Evolution of the Circle of Uncertainty

Figure 2 is somewhat misleading, however. Consider Figure 3. On the left, the evolution of the circle of uncertainty for the robot's location is shown. In the middle, three potential locations are shown for the three changes of direction.

Although these locations all fall within the relevant circles of uncertainty, the robot could never get to the third location from the second. This is because, as depicted on the right of the figure, in any given model the circle of uncertainty for the robot's location at the end of a period of continuous motion can only be defined relative to its actual location at the start of that period. This can be verified by inspecting Axioms (B7) and (B8).

The relative nature of the evolution of the circle of uncertainty means that the robot can acquire a detailed knowledge of some area A1 of its environment, then move to another area A2 which is some distance from A1, and acquire an equally detailed knowledge of A2. The accumulated uncertainty entails only that the robot is uncertain of where A1 is relative to A2. This natural feature of the formalisation conforms with what we would intuitively expect given the robot's informatic situation.

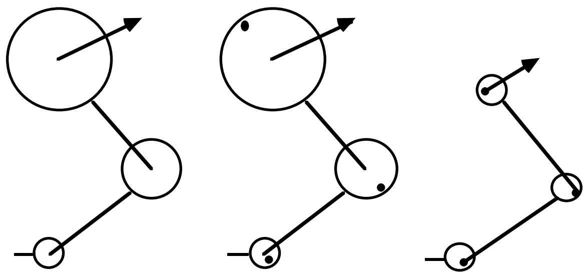

Figure 3: The Circle of Uncertainty Is Relative Not Absolute

In the presence of non-determinism, the abductive account of sensor data assimilation presented in Section 2 will not work. The next section presents a modified characterisation which overcomes the problem.

4 Non-Determinism and Abduction

Non-determinism is a potential source of difficulty for the abductive approach to explanation. Even with a precise and complete description of the initial state of the world, including all its objects and their shapes, a non-deterministic theory incorporating a formula like (B7) will not yield the exact times at which collision events occur. Yet the sensor data to be assimilated has precise times attached to it.

Fortunately we can recast the task of assimilating sensor data as a form of *weak abduction* so that it yields the required results. Intuitively what we want to capture is the fact that without the hypothesised objects, the sensor data could not have been received. This is analogous to the consistency-based approach to diagnosis proposed by Reiter [1987].

Definition 4.1. Given,

- the conjunction B of CEC with Axioms (B1), (B2), and (B4) to (B8),
- the conjunction E of Axioms (E1) to (E6),
- the conjunction O of Axioms (Sp1) to (Sp8),

- a conjunction M1 of Initially formulae describing the initial locations, shapes, and orientations of known objects, including the robot itself,
- the conjunction N1 of Axioms (H1) to (H3),
- a conjunction N2 of Happens formulae describing the robot's actions, and
- a conjunction Ψ of formulae of the form Happens(Switch1,τ) or Happens(Switch2,τ),

an *explanation* of Ψ is a conjunction M2 of formulae in which each conjunct has the form,

$\exists$ g [Initially(Occupies(ω,g)) $\wedge$ $\forall$ p [p $\in$ g $\leftrightarrow$ Π]]

where ω is an object constant and Π is any formula in which p is free, such that O $\wedge$ M1 $\wedge$ M2 is consistent, and,

CIRC[O $\wedge$ M1 $\wedge$ M2 ; AbSpace ; Initially] $\wedge$
CIRC[N1 $\wedge$ N2 ; Happens] $\wedge$
CIRC[E ; Initiates, Terminates, Releases] $\wedge$ B $\nvDash$
$\neg$ [Ψ $\wedge$ COMP[Ψ]]. □

There will, naturally, be many explanations for any given Ψ which meet this definition, even using the boundary-based representation of shape adopted in the full version of the paper. A standard way to treat multiple explanations in abductive knowledge assimilation is to adopt their disjunction [Shanahan, 1996a, Chapter 17]. This has the effect of smothering any explanations which are stronger than necessary, such as those which postulate superfluous obstacles. The disjunction of all explanations of Ψ is the *cautious explanation* of Ψ.

A variety of *preference relations* over explanations can also be introduced. For example, it might be reasonable to assume that nearby collision points indicate the presence of a single object. Such preference relations are a topic for further study.

The following theorem establishes that the above definition of an explanation is equivalent to the deterministic specification offered in Section 2 when ε is 0. Let B_{det} be the conjunction of CEC with Axioms (B1) to (B6).

Definition 4.2. A formula M is a *complete spatial description* if the region occupied by each object mentioned in M is the same in every model of,

CIRC[O $\wedge$ M ; AbSpace ; Initially]. □

Theorem 4.3. If ε = 0 and M1 is a complete spatial description, then M2 is an explanation of Ψ if and only if O $\wedge$ M1 $\wedge$ M2 is consistent and,

CIRC[O $\wedge$ M1 $\wedge$ M2 ; AbSpace ; Initially] $\wedge$
CIRC[N1 $\wedge$ N2 ; Happens] $\wedge$
CIRC[E ; Initiates, Terminates, Releases] $\wedge$ B_{det} $\vDash$
Ψ $\wedge$ COMP[Ψ].

Proof. See full paper. □

To illustrate the new definition, suppose the robot behaves as illustrated in Figure 4. Let N2 be the conjunction of the following formulae, which represent the robot's actions up to and including the time it bumps into obstacle A.

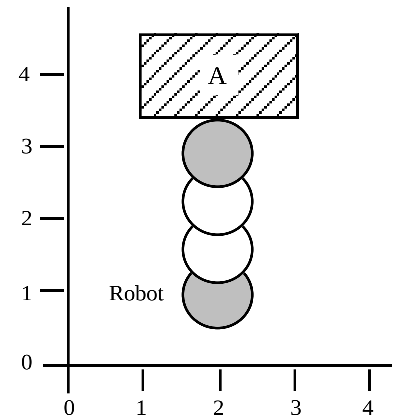

Figure 4: The Robot Collides with an Obstacle

Happens(Go,0) (4.4)

Happens(Stop,2·1) (4.5)

Let M1 be the conjunction of the following formulae.

Initially(Facing(0)) (4.6)

Initially(Occupies(Robot, Displace(Disc(0·5),⟨2,1⟩))) (4.7)

Let M2 be the following formula.

$\exists$ g [Initially(Occupies(A,g)) $\wedge$
$\forall$ x,y [⟨x,y⟩ $\in$ g $\leftrightarrow$ 1 < x < 3 $\wedge$ 3·5 < y < 4·5]] (4.8)

In the noise-free case, the robot would collide with A at time 2·0. However, let's assume the collision takes place at time 2·1. Let Ψ be the conjunction of the following formulae.

Happens(Switch1,2·1) (4.9)

Happens(Switch2,2·1) (4.10)

Let ε be 0·25. The following proposition says that M2 is indeed an explanation of Ψ according to the new definition.

Proposition 4.11.

CIRC [O $\wedge$ M1 $\wedge$ M2 ; AbSpace ; Initially] $\wedge$
CIRC[N1 $\wedge$ N2 ; Happens] $\wedge$
CIRC[E ; Initiates, Terminates, Releases] $\wedge$ B $\nvDash$
$\neg$ [Ψ $\wedge$ COMP[Ψ]].

Proof. See full paper. □

Concluding Remarks

A considerable amount of further work has been carried out, which is reported in the full version of the paper, but which it is only possible to present in outline here. Two further theorems have been established which characterise the abductive explanations defined above in terms which appeal more directly to the information available to any map-building algorithm which might be executed on board the robot. These theorems have been used to prove the correctness, with respect to the abductive specification given, of an algorithm for sensor data assimilation which constructs an *occupancy array* [Davis, 1990, Section 6.2.1].

This algorithm forms the core of an implementation in C, which runs on data acquired by the robot in the real world. Some preliminary experiments have been conducted in which the robot, under the control of a behaviour-based architecture [Brooks, 1986], explores an enclosure, and makes a record of its actions and sensor data for subsequent processing using the algorithm.

In the paper accompanying his 1991 Computers and Thought Award Lecture, Brooks remarked that,

> [The field of Knowledge Representation] concentrates much of its energies on anomalies within formal systems which are never used for any practical task.
>
> [Brooks, 1991a]

The work presented in this paper and in [Shanahan, 1996b] should be construed as an answer to Brooks. According to the logical account given in this paper, a robot's incoming sensor data is filtered through an abductive process based on a framework of innate concepts, namely space, time, and causality.[1] The development of a rigorous, formal account of this process bridges the gap between theoretical work in Knowledge Representation and practical work in robotics, and opens up a great many possibilities for further research. The following three issues are particularly pressing.

- The assimilation of sensor data from moving objects, such as humans, animals, or other robots. Movable obstacles should also be on the agenda.
- The assimilation of richer sensor data than that supplied by the Rug Warrior's simple bump switches.
- The control of the robot via the model of the world it acquires through abduction.

Future implementation is expected to adopt a logic programming approach. Existing work in the Cognitive Robotics vein is likely to be influential here [Lespérance, *et al.*, 1994], [Kowalski, 1995], [Poole, 1995].

Acknowledgements

The inspiration for Cognitive Robotics comes from Ray Reiter and his colleagues at the University of Toronto. Thanks to Neelakantan Kartha and Rob Miller. The author is an EPSRC Advanced Research Fellow.

References

[Bacchus, *et al.*, 1995] F.Bacchus, J.Y.Halpren, and H.J.Levesque, Reasoning about Noisy Sensors in the Situation Calculus, *Proceedings IJCAI 95*, pages 1933-1940.

[Brooks, 1986] R.A.Brooks, A Robust Layered Control System for a Mobile Robot, *IEEE Journal of Robotics and Automation*, vol 2, no 1 (1986), pages 14-23.

[Brooks, 1991a] R.A.Brooks, Intelligence Without Reason, *Proceedings IJCAI 91*, pages 569-595.

[Brooks, 1991b] R.A.Brooks, Artificial Life and Real Robots, *Proceedings of the First European Conference on Artificial Life (1991)*, pages 3-10.

[Davis, 1990] E.Davis, *Representations of Commonsense Knowledge*, Morgan Kaufmann (1990).

[Jones & Flynn, 1993] J.L.Jones and A.M.Flynn, *Mobile Robots: Inspiration to Implementation*, A.K.Peters (1993).

[Kowalski, 1995] R.A.Kowalski, Using Meta-Logic to Reconcile Reactive with Rational Agents, in *Meta-Logics and Logic Programming*, ed. K.R.Apt and F.Turini, MIT Press (1995), pages 227-242.

[Lespérance, *et al.*, 1994] Y.Lespérance, H.J.Levesque, F.Lin, D.Marcu, R.Reiter, and R.B.Scherl, A Logical Approach to High-Level Robot Programming: A Progress Report, in *Control of the Physical World by Intelligent Systems: Papers from the 1994 AAAI Fall Symposium*, ed. B.Kuipers, New Orleans (1994), pages 79-85.

[McCarthy, 1989] J.McCarthy, Artificial Intelligence, Logic and Formalizing Common Sense, in *Philosophical Logic and Artificial Intelligence*, ed. R.Thomason, Kluwer Academic (1989), pages 161-190.

[Nilsson, 1984] N.J.Nilsson, ed., *Shakey the Robot*, SRI Technical Note no. 323 (1984), SRI, Menlo Park, California.

[Poole, 1995] D.Poole, Logic Programming for Robot Control, *Proceedings IJCAI 95*, pages 150-157.

[Reiter, 1987] R.Reiter, A Theory of Diagnosis from First Principles, *Artificial Intelligence*, vol 32 (1987), pages 57-95.

[Shanahan, 1989] M.P.Shanahan, Prediction Is Deduction but Explanation Is Abduction, *Proceedings IJCAI 89*, pages 1055-1060.

[Shanahan, 1995a] M.P.Shanahan, Default Reasoning about Spatial Occupancy, *Artificial Intelligence*, vol 74 (1995), pages 147-163.

[Shanahan, 1995b] M.P.Shanahan, A Circumscriptive Calculus of Events, *Artificial Intelligence*, vol 77 (1995), pages 249-284.

[Shanahan, 1996a] M.P.Shanahan, *Solving the Frame Problem: A Mathematical Investigation of the Common Sense Law of Inertia*, MIT Press (1996), to appear.

[Shanahan, 1996b] M.P.Shanahan, Robotics and the Common Sense Informatic Situation, *Proceedings ECAI 96*, to appear.

[Strawson, 1966] P.F.Strawson, *The Bounds of Sense*, Methuen (1966).

[1] This is somewhat reminiscent of Kant, according to whom, "the natural world as we know it . . . is thoroughly conditioned by [certain] features: our experience is essentially experience of a spatio-temporal world of law-governed objects conceived of as distinct from our temporally successive experiences of them" [Strawson, 1966, page 21].