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Biologically inspired navigation primitives

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HIGHLIGHTS

- The trajectories of Braitenberg vehicles are modelled as a nonlinear dynamical system.
- Intuitive understanding of these vehicles can be explained through the model.
- Local stability of the trajectories can be analysed for general stimuli.
- Given a desired behaviour, conditions for stimulus design can be obtained.
- Simulations illustrate and confirm the theoretical results.

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ABSTRACT

Because of their apparent simplicity, Braitenberg vehicles have been extensively used in robotics on an empirical basis. However, the lack of a backing up formal theory turns their application into an educated guess of parameter tunning. This paper provides a mathematical model of Braitenberg vehicles 2 and 3 as non-linear dynamical systems, which serves as a theoretical ground to fully exploit them for robotic applications and to create animated agents in artificial life or computer games. The behaviour of the vehicles is analysed using theory of dynamical systems under general conditions, and hints on how to generate desired behaviours are given. Results show that vehicles 2 and 3 can be used to implement bio-inspired navigation like; target reaching and stimulus avoidance, which constitute a set of navigation primitives or basis for navigation behaviour. Through a new theoretical approach, this work paves the way to a proper understanding of Braitenberg vehicles and to an extension of their applicability.

1. Introduction

Braitenberg vehicles [1] qualitatively model sensor based animal steering, and have long been used on an empirical basis in robotics. The simplest Braitenberg vehicles model the motion of animals towards, or escaping from, a stimulus, known in biology as (positive or negative) taxis behaviour [2]. Animals are very good at moving in the real world and, therefore, they can represent a good model to follow when implementing robotic motion as reflected by the multiple successful empirical applications of Braitenberg vehicles to robotics. While positive taxis is a goal seeking technique, negative taxis implements avoidance behaviours, both form a basis, or primitives, of navigation behaviour in mobile robots. Because of their simplicity, they are easily understood at an intuitive level without the need of a strong mathematical background, but this is not enough to exploit their full potential. In fact, as a control mechanism for wheeled robots, they are easier to understand by the newcomer to robotics that potential field approach based techniques, and that is why they are sometimes used for teaching [3,4].

By building up vehicles with sensors wired to their wheels, Braitenberg models complex biological behaviours with great simplicity. Wheels abstract locomotion to focus on steering or guidance level [5], therefore, they can model locomotive configurations like walking, swimming or crawling under standard forward motion conditions. This simplifies the control and analysis of motion, and is a good approximation as forward moving animals, like wheeled vehicles, suffer from non-holonomic restrictions to motion [6]. Braitenberg vehicles can, therefore, be used to design robotic controllers at the steering level. The sensors used by Braitenberg vehicles perceive an abstract stimulus at some point, though the stimulus could also be an artificial potential function. To simulate the omni-directionality of the sensors many empirical applications of Braitenberg vehicles include rings of sensors around the robot.

As shown in Fig. 1, vehicles 2 and 3 simply consist on direct or crossed connections between the sensors and the motors. Some

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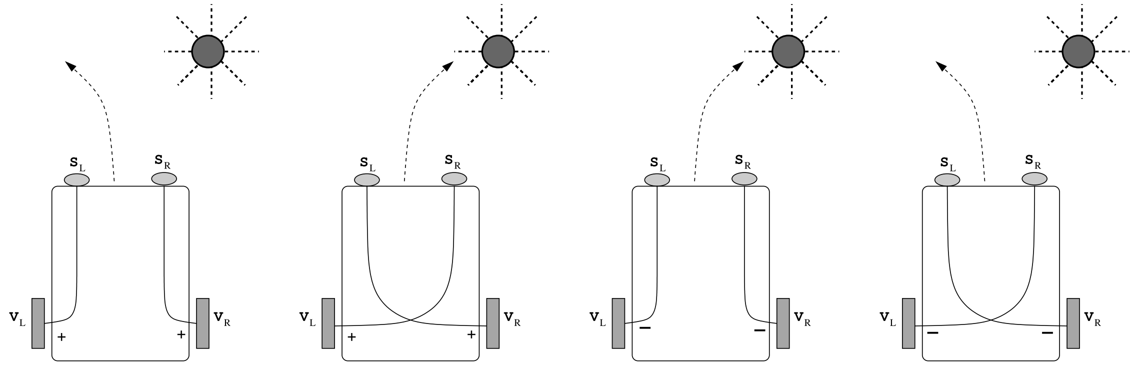

(a) Vehicle 2a. (b) Vehicle 2b. (c) Vehicle 3a. (d) Vehicle 3b.

Fig. 1. Schematics of Braitenberg vehicles 2 and 3.

vehicles have increasing connections such that a stronger stimulus in the sensor generates a faster turn of the associated wheel, while others have a decreasing connection. These vehicles are immersed in environments with a unique kind of stimulus they can perceive. This simplifies the analysis and design of their behaviour while serves as building blocks for more complex vehicles. The combination of direct, crossed, increasing and decreasing connections between the sensors and the wheels of the vehicles generates four different vehicles as presented in Fig. 1. When sensors on one side are connected to the motors on the same side (ipsilateral) we will talk about a-type or parallel vehicles, while b-type vehicles display a crossed (contralateral) connection as depicted in Fig. 1(b) and (d). Vehicles 2 have an increasing or excitatory connection linking perception to action, represented by the '+' sign in Fig. 1(a) and (b), while for vehicles 3 the connection is decreasing or inhibitory [7].

The behaviour of each vehicle can be qualitatively analysed assuming that a stimulus source in the environment generates a distance decreasing scalar field. Basically, intuition dictates that vehicles 2b and 3a will move towards high values of the stimulus, and vehicles 2a and 3b will head towards lower values, but sometimes intuition fails in explaining their behaviour [8]. While vehicles 2 might move faster next to the stimulus source, vehicles 3 will slow down as they get close to high stimulus intensity because of the decreasing connection. All these vehicles intuitively generate gradient descent or hill climbing trajectories, while accounting for the non-holonomic constrains to their motion. The simplicity of the control mechanism makes it biologically plausible, while at the same time it is argued [1] that they can produce quite complex behaviours depending on the specific stimulus and internal wiring between sensors and motors.

As we will see, multiple empirical applications of Braitenberg vehicles can be found in the literature; target seeking, wandering, sound, light or gas source localisation and obstacle avoidance. This paper contributes to the general knowledge of Braitenberg vehicles by delivering a joint mathematical model of the control mechanisms of vehicles 2 and 3, and therefore providing theoretical support for these empirical works. Although some behaviour analysis of vehicles 2b and 3a has been presented elsewhere, this paper provides a more exhaustive analysis of all the possible stability conditions, while it also includes vehicles 2a and 3b, not considered in previous works. Moreover, based on this model, new applications can be found [9,10] for sensor driven robot steering. We use dynamical systems theory to analyse their behaviour, show new theoretical results of their motion and derive design principles to obtain a desired behaviour. Simulations are presented to illustrate the theoretical results.

The paper is organised as follows. The rest of this section presents some robotics applications of Braitenberg vehicles that can be found in the literature. Section 2 states the working assumptions, presents the corresponding mathematical models of the controllers and proposes an analysis that justifies our empirical understanding of Braitenberg vehicles. Section 3 derives general properties of the behaviour of the vehicles, and states additional assumptions that help designing effective controllers for Braitenberg vehicles. The simulations to illustrate the properties of the vehicle trajectories are presented in Section 4. To conclude the paper, a summary of the results, their implications and further working lines are presented in Section 5.

1.1. Related works

Different Braitenberg vehicles have been successfully used on an experimental basis to provide mobile robots with several abilities. However, the lack of a theoretical understanding of this bio-inspired controllers limited their potential applications. Vehicles 3a and 3b for odour source localisation are analysed from an experimental point of view in [11], where the connection between sensors and motors is linear but sensor readings are normalised and averaged. Due to the nature of the stimulus and sensing hardware, a necessary sensor preprocessing introduces a dynamic component in the connection. This is the first application of Braitenberg vehicles to chemical source localisation, a highly complex problem since the stimulus changes with the robot motion. Phonotaxis in a robotic rat is presented in [12] through a model of the peripheral auditory system in mammals. The main contributions of this work are the simplification of sound source localisation through the pinnae and the cochlea model, and a successful implementation of a model of the central auditive system, with a Braitenberg vehicle 3a to control the robot motion. Another example of phonotaxis behaviour is presented in [13], where the auditory system of a lizard is implemented. In fact, their model of the lizard ear is good enough to work with a high success rate over a wide range of frequencies using a Braitenberg vehicle 2b and a bang–bang controller. Interestingly, the performance of both controllers was similar even though they did not have a model of the vehicle to tune the behaviour of the robot. In a series of works [14–16] a female cricket phonotaxis model is implemented using spiking neural networks connected according to the excitatory and inhibitory principles of Braitenberg vehicles. This neural model of motion control is comparable to a combination of vehicles 2a and 3b, since excitatory units display a parallel connection between sensors and motors, while inhibitory ones are crossed. The authors prove their robots perform very well even under quite adverse outdoor conditions. The first robotic implementation of rheotaxis is presented in [10], where a fish robot provided with pressure sensors can keep its orientation relative to a laminar flow. Even though the forward speed is kept fixed, the turning rate of the fish is computed following the