Behavioral analysis of multi-agent systems of Braitenberg vehicles

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*Abstract*—The potent idea behind the Braitenberg vehicles can be used for a wide variety of applications such as target approaching, path navigation, transportation motivated due to various stimuli in the environment. This paper moves around this idea and models a variety of different robots/vehicles tested in a 3D simulated environment to judge the fitness and intelligence of a group of inspired Braitenberg vehicles. Various experiments are designed in a way that helps evaluate useful traits that emerge out of a multi-agent system of vehicles.

Keywords—Braitenberg vehicle, simulation, multi-agent, deadlock, behaviour coordination

# Introduction

There is a variety advanced robot available now that possess many capabilities due to increasing degree of embodiment but the motive of creating simple internal structure that could possibly demonstrate not just complex but dynamic behaviour is what actuated this experimental study. The motivation of this paper is also to simulate a kind of social interaction among more numbers of different kind of vehicles and observe what interesting traits can be derived from this setup. The simulation also revolves around the basic instinct to saving oneself from a dangerous situation such as collision. This paper also classifies the two incidents such as collision and excitement by light as either a dire necessity or just an interest from the viewpoint of the robot. It is very natural when any organism faces a dangerous situation, it will only react to save itself even though there are many things that attract them in their surrounding at the moment. The design of the behaviours for the robot is made keeping in mind this very animal instinct. A form of pseudo Fixed Action Pattern is also encoded as the behaviour of the robot to model a more predictable behaviour for the robot.

Also, to sense the environment for dangerous situation the robot should have necessary channels or sensors. As the robot is embedded with a sensor to detect the collision, the capabilities of the robot increase meaning the degree of embodiment also increase making the robot comparably smarter than the robots without these sensory input channels. But, the study also observes the usage strategy of the sensor also impact the intelligence of the robot to take better decisions.

# Background

## Braitenberg vehicles [1]

The idea, Valentino Braitenberg present in his book “Vehicles: Experiments in Synthetic Psychology”, that complex and dynamic behaviour can be obtained through simple “neurological” connections is the basis of this paper. This thought experimental idea is very potent. These vehicles with a simple internal structure deliver a very unpredictable and complex behaviour at times because their motion/movement is a result of all the forces exerting on it through the environment as they are not meant to be run in the space, said so in the book.

This idea tries to model the animal world with minimalistic and simple design where the vehicle is driven by simple taxis behaviour to external stimulus such as light, temperature, etc. To mimic the complex behaviours showcased by animals, we don’t to recreate the whole complex structure but a simple internal organization is enough for it. If one looks at these vehicles externally without explicitly knowing its internal structure, one may think that the vehicle is intelligent as it can show behaviours such as love, aggression, curiosity, admiration, shyness, fear etc.

To set a strong basis for this paper, let us discuss some original Braitenberg vehicles proposed in the book, “Vehicles: Experiments in Synthetic Psychology”. To obtain different vehicles which showcase a wide array of behaviours combination of different values of the following parameters is used:

* Number of wheels and sensors.
* Connection between the sensors and the motors/wheels.
* Activation function of the motor.

1. *Vehicle 1 [1]*

The vehicle 1 has the simplest internal structure. It has one motor connected to one wheel at the rear and one sensor to detect the light (or even temperature) in the front. The vehicle is subject to Brownian motion where its motion is based on all the forces the environment exerts on it such as frictional force, gravity, etc. It can either stand still or keeping moving. Again, the motion is generally in the straight direction unless the direction is changed due to any perturbation by the environment.

The motor is connected to the sensor. The speed of the motor is controlled by the sensor and is directly proportional to the sensor input. If the sensor detects light the speed of the motor increases causing the vehicle to move forward with increasing speed in the straight direction towards the source of light. If the source of light is in the straight line to the vehicle it reaches it with great speed and stops as it reaches the light source. If the light source is not exactly in the straight line to the moving vehicle it will move with increasing speed in the forward direction until it passes the light source and stops moving when the sensor is out of range of the light source.

From this behaviour towards light source, one might say that the vehicle is calm when there is no light but as soon as it senses light it starts moving faster. Also, andromorphically speaking one might say that the vehicle 1 is not very fond of the light because it gets restless in the presence of light.

1. *Vehicle 2a – Fear [1]*

The Vehicle 2a has two motors driving two wheels separately at the rear with two light sensors at the front. The left sensor is connected to the left motor and the right sensor is similarly connected to the right motor. The speed of the motors is directly proportional to the intensity of light detected by the sensors. The motion is now just limited to back and forth but Vehicle 2a can also make turns if the velocity of both the wheel is not the same.

If the light sensor is directly in the straight line to the vehicle 2a, it behaves similarly to Vehicle 1 as the light sense by each light sensor is the same. This case changes when the vehicle is not in the straight line to the light source. The sensor which is nearer to the light source is excited more than the one away from it. Subsequently, the motor connected to the light sensor near to the light source (same side of the vehicle) has greater speed compared to the one away from the light source. The wheel moving with greater speed will cause the vehicle to turn away from the light source at a great speed initially but the speed diminishes as the vehicle moves away from the light source and halt when it is facing away from the light source or the moment the sensors could not sense any light.

Without knowing the internal structure of the system, it can be commented that the vehicle 2a showcases fearful or shy behaviour towards light.

1. *Vehicle 2b – Aggression [1]*

Similar to Vehicle 2a, Vehicle 2b also has two motor attached to two wheels separately at the back side of the vehicle with two light sensors attached in the front for sensing light. The speed of the motor depends directly on the intensity of the light sensed by the sensor. The connection between the sensors and the motors is crossed, meaning that the left sensor is connected to the right motor and right sensor is connected to the left sensor. Again, if the vehicle is placed initially in the line towards the light it behaves exactly the same way as the vehicle 1 and 2a. The behaviour differs when the vehicle is place anywhere but in the straight line to the light. The wheel near the light source gains lesser magnitude of speed compared to one away from the light source as the wheel away from the light source is connected to the sensor nearer to the light source. This makes the vehicle turn and move towards the light source with increasing speed and collide with it with greater speed and halt right there.

Again, one who does not know anything about the internal mechanical circuitry might think that this vehicle 2b is very aggressive towards the light source and heads on collide with it.

1. *Vehicle 3a – Love/Admiration [1]*

Vehicle 3a has the same internal connection as Vehicle 2a. The only difference is that the activation function of the motor is negative or inhibitory, meaning the speed of the motor is negatively proportionate to the intensity of light sensed by the sensors.

Here, the difference is that the initial speed of the vehicle is maximum and it decreases in the presence of light depending some the intensity of the light. In absence of any light source, the vehicle moves at maximum speed. When the light is in the straight line to the vehicle approaches it with decreasing speed and stops at a distance from the light when the activation speed is equal to the maximum speed. When the vehicle is anywhere but in the straight line to the light, the light sensor near to the light source is excited more compared to one far away causing the wheel near to the light source to slow down and the one far from it has still greater speed compared the other one. This will make the vehicle turn towards the light source and approach it will decreasing speed until stopping at a distance facing the light source. The vehicle remains in this position until there is a perturbation from the environment.

Here, anthropomorphically one can comment that the vehicle’s behaviour showcases admiration/love for the light. It moves to the light slowly and watches it from a distance as if admiring the light’s beauty.

1. *Vehicle 3b - Exploration [1]*

Vehicle 3b is very similar in the internal structure to 2b with the same crossed connection of sensors and motors but with an inhibitory activation function where the speed of the motor is inversely proportionate to the intensity of light sensed. When the light is placed in the straight line to the light, it behaves exactly like Vehicle 3a and stops at a distance from the light. This behaviour changes when the vehicle is not facing the light directly. The vehicle is initially moving with maximum speed in absence of light and when it encounters light (at an angle) it will slow down. It will slowly turn away from the light source. The speed increasing as it goes farther from the light source. It turns away from the light source due to the correct connection and the inhibitory activation function.

The anthropomorphic comment on this vehicle can be that it is fascinated by the light source and slows down to look at it for a while with first increasing and then decreasing interest before it shoots off to find another light source. This behaviour can be summed up as exploration or curiosity.

## Embodiment

Embodiment has been arguably the one of the reasons for intelligence in robot. [2] Embodiment is realized through sensors and effectors embedded in robot because a robot is said to be embodied is it is capable to interact with the environment and the state of environment in one or the other way. Similarly, the state of robot should also be changed by the environment. This strong coupling and structural variability results in an intelligent robot which is embodied and is more capable of sensing its environment.

Increasing embodiment means increasing the number and types of sensors such as light sensor, touch sensor, temperature sensor, camera, etc. to better perceive the environment to gather various inputs from the environment and also increasing number and types of effectors/actuators such as wheels, limbs, speaker, etc. to better interact with the environment and to increase the capabilities of the robot such as moving around, speaking, lifting things, etc.

## Behaviour Coordination Architecture

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When a robot has more than one behaviour and responses to different stimuli, it might be difficult to figure out which behaviour will be triggered in presence of multiple stimuli. To resolve the conflict between the behaviours various coordination architecture are proposed, two major types are as follows:

1. *Competitive Behaviour Coordination Architecture*
2. *Cooperative Behaviour Coordination Architecture*
3. *Hybrid between Competitive and Cooperative*

The most significant distinction between competitive and cooperative robot coordination architecture is that in competitive robot coordination, only one behavior's reaction always wins. There is priority-based coordination between all behaviours in competitive behavioural coordination. In the case of cooperative behavioural coordination, a behavioural fusion via vector summation technique is used. In competitive robot coordination, there is a hierarchy-based dominance of behaviours. With inhibition and suppression of other behaviours, one behaviour is given priority over the others. All of the behaviours compete to give the robot a response. Whereas, in the situation of cooperative coordination, there is behavioural fusion with no priority or hierarchy. Each behaviour vector is given a weight, which is then utilised to calculate the cooperative robot coordination response. The weights are assigned in accordance with the robot's intended goal. There are ways, called the hybrid coordination, to combine these two approaches such as Voting Based Coordination and Activation Selection Coordination.

## Fixed Action Pattern [3]

Fixed action pattern is an innate sequence of predictable actions that are triggered due to a key stimulus or releaser. This sequence of actions is highly structured and rigid, meaning it does not change based on the intensity of the stimulus. Once this sequence is triggered, it runs to completion regardless of removal of the key stimulus or any change in the environment.

# Technology Used

All the experiments mentioned in this paper are simulated in Webots [4] 3D Simulator, which is an open source and multi-platform desktop software. It comes adorned with a plethora of sensors and actuator that are used for robot simulation such as distance sensors, light sensors, touch sensors, lidars, radars, etc. It supports robot controller written in languages such as C, C++, Python, Java, etc.

The controllers for all the robots/vehicles in all the experiments for the paper is written in Python (version 3.8.10). The sensors used in the experiments are the in-built sensors available in Webots. The detailed documentation of how to use each sensor is readily available online on Webots own tutorial site. All the simulations in these experiments are three dimensional.

The usage of Webots is preferred for performing the simulation experiments is because of the ease of use and readily available detailed documentation of sensors and environment. Python is chosen for the coding the controllers of the robots because of the familiarity of the language as well compatibility of the language versions with the simulator. Additionally, because the language is popularly growing and has a huge community support for debugging.

# Stimuli and Sensors

The main focus of these experiments is to observe the collective behaviour of a group of Braitenberg vehicle in presence of multiple stimuli. It is a fact that the size of the arena is limited for the experiment so when there is more than one vehicle that are attracted or repelled by light that are bound to collide at one point in time. The collision can take place immediately as they start moving in response to light as a stimulus or it happens later as they start moving around the arena for quite a while. It brings out the need to list the factors of the environment that can affect the robot in these experiments. The stimuli a robot is affected by are:

* Light: This is simulated using PointLight [5] in Webots. The property of PointLight is that it is attenuated according to the distance between the sensor and the light.
* Collision with any object in the environment including any stationary objects, other moving vehicles or the walls of the arena of the simulated world.

Increasing embodiment, in form of introducing one more sensor compared to the original Braitenberg vehicles, is a necessity here to sense these stimuli and react to them, the robots in these experiments are facilitated with two kinds of sensors which are as follows:

## LightSensor [6]

It senses the light in the vicinity of the robot. It measures the irradiance of light in any given direction that falls directly on it. [citation-needed] Irradiance, often known as intensity, is the radiant power incident on a surface measured in watts per square metre [W/m2]. In the simulated world, the irradiance is computed by summing up all the irradiance by all the light sources in the world. Any reflected light is not sensed by the Light Sensor.

## TouchSensor [7]

There are in total three kinds of TouchSensor provided by Webots: "bumper", "force", and "force-3d". In these series of experiment, only the “bumper” kind, the simplest of all three, is used. The bumper TouchSensor return 1.0 value when collision is detected and 0.0 otherwise. The collision is detected when the bounding object [8] of the vehicles sensor is overlapping or intersected with the bounding object of any other (solid) object in the environment. Bounding objects are essentially used in Webots for collision detection purpose. Bounding objects defines the geometric primitives for detecting collisions.

# Modeled Behaviours and The Coordination Architecture

## Modeled Behaviours

There are in total three new modeled behaviours for the robots that are experimented. These behaviours are modeled keeping in mind the goal of the experiments that is to observe the dynamic emergent nature of the group of robots or individual robot. To make the behaviour interesting and notable, the robots other than the original Braitenberg vehicles mentioned in Background section, designed to move about arena even in absence of any stimuli. There are three basic behaviours that applies to the derived Braitenberg vehicle/robot inspired by the original ones:

### Wander: In absence of any stimuli, the robot will keep wandering around with a predefined constant speed to find some stimulus that excites it. There two strategies that has been implemented in this paper for this behaviour: move with minimum reasonable speed such as 1 or move with maximum speed permitted by Webots which is 10. This behaviour is modeled to keep the robot moving in search of stimulus.

### Phototaxis: This is the same behaviour that is exhibited by the original Braitenberg vehicles. There are two possible behaviour: Attraction and Repulsion towards the light. This is modeled with different combinations of connection between motors and light sensors (direct or crossed) and activation function (positive and negative).

### Back and Turn Away (BTA): This behaviour is modeled to trigger only when there is a collision. It is modeled to correct the collision and move away from the object it collided with. A simple method to correct collision is moving back from the place of collision and then turn in other direction to avoid colliding with it again assuming that the object of collision is stationary. But, the mechanics of the optimal turn to make depends on variety of factor but the robots only have two sensors (light and touch) so it is incapable of deciding the size of the obstacle hence it is not possible for the robots here to avoid colliding with the obstacle at once. It may take several attempts before it can move past it depending upon the size of the obstacle. There are two strategies implemented for this behaviour:

#### Fixed action pattern strategy: Here, the sequence of action will always remain the same regardless of the situation after collision is detected. For example, the robot moves back 5 steps and then turn in left direction of 5 steps. It will do so under any condition once it detects collision. This is similar to Fixed action pattern because regardless that once it moves one step back there is no longer any collision yet it runs the routine to completion once triggered. The limitation of this strategy is the robot might run into a dead zone or deadlock as the routine is rigid. It might get stuck between two stationary object and would not be able to move out of the dead zone.

#### Randomized strategy: Here, the BTA is randomized to avoid dead zones/ deadlocks. Even if the object gets stuck somewhere the strategy is modeled in such a way that it will traverse out of the dead zone even if it takes the robot multiple tries. The randomization is applied in the duration the BTA is in effect, the sharpness of the turn, and the direction of the turn. This helps in relieving symptoms of deadlock.

## The Behaviour Cooordination Architecture for the modelled bhevaiours

The modeled behaviours follow Competitive Coordination Architecture. This is inspired by the basic instinct of animal to choose its survival before any other behaviour. (This may not be the case in all the animals, but surely in some of them.) The hierarchy or priority is given as follows, the first being the one highest priority with decreasing priority, the last being the least of priority:

1. *Back and Turn Away*
2. *Phototaxis*
3. *Wander*

The hierarchy is steered in this way because collision is not a favourable situation for the robot and as soon as it collides, it needs to correct before damaging itself more. Then, phototaxis is what drives the original Braitenberg vehicle and is important to understand the behaviour of the vehicle/robot. The last is Wander which is only in effect when there are no other stimuli present and its goal is to search for the stimuli.

# Experiments and Results

The results of the experiments below are based on the generalization of multiple runs of the same experiment setup with a minor tweaking such the initial position of the vehicles, changing intensity of the light source, moving the stationary objects around, etc.

## Experiment 1: Multiple Light source and a single robot.

In the first experiment, multiple light sources with varying intensity value where placed in the arena and an aggressive robot without any TouchSensor was placed in the simulation.

Result: The robot moves collectively around the light sources encircling them. The curvature of this circle depends on the intensity value of the light. The more the intensity value greater the radius of the circle traversed by the vehicle around it. Also, the behaviour depends on the initial placement of the vehicle. If the vehicle is placed in the straight line to any of the light sources, it tends to ignore the rest and tries to collide with the light source.

## Experiment 2: Multiple Light sources with multiple stationary obstacles/objects and multiple vehicles of different kinds.

The vehicles used in this experiment are the variants of Braitenberg vehicle 2b and 3b. The three variants are called:

1. *Depressed Aggressor:* Vehicle 2b with TouchSensor and fixed BTA behaviour. Wander behaviour is depressed as it only moves with speed of 1 in absence of light source.
2. *Curious/Eager Aggressor:* Vehicle 2b with TouchSensor and randomized BTA behaviour. Wander behaviour is eager as it moves with the maximum speed when it can not sense any light. Hence, it can be said that this aggressor is eagerly searching for light and once it encounters it is influenced by the light source the same as original vehicle 2b.
3. *Explorer:* Vehicle 3b with TouchSensor and fixed BTA behaviour. It does not need the Wander behaviour as its initial speed is maximum.

The arrangement of the vehicles is shown in Fig. 6. The intensity of two light sources closer to the walls is greater than the rest to observe if the robots are attracted to these light sources as they are brighter. Initial position of the robots is in the middle and corner without light source to observe their navigation to the light sources.

Result: The explorers avoid the light source and gather at the walls in attempt to escape the arena to explore more. The behaviour of depressed aggressor is more predictable compared to eager aggressor as the BTA behaviour is fixed in the case of depressed aggressor and randomized for the latter. The explorer does not really interact with the other types of vehicles but start poking at the walls. The other two types of vehicles move from one source of light to the other as a result of attraction to light with higher intensity and due to collision with other vehicles near them. The average collision rate is compared as follows:

Eager Aggressor >> Explorer > Depressed Aggressor

This can be explained using simple interpretation of their behaviour. Eager Aggressor has maximum collisions because of its eager nature that it moves speedily when it can not find light sources making it prone to more collisions. Also, the randomized BTA behaviour makes its traversal path unpredictable which is likely to intersect with other vehicles’, mostly its own kind, path and collision occurs more frequently. Explorer has the most consistent collision rate as all the explorers are lined up by the wall constantly poking at the wall which gets them to the second position in the comparison. The depressed aggressor is slower and has a fixed BTA behaviour which makes it very much predictable and it does not cross path with other vehicles more often.

## Experiment 3: “Maze Runner”

This experiment is the final one in this series of experiment aiming to see how intelligently these vehicles can achieve a complicated goal such as finding its way to the light through a maze as shown in Fig. [reference to fig needed]. This experiment is designed in form of a competition between two vehicles: Eager Aggressor and Depressed Aggressor. The aim of this experiment is to see which vehicle is successful in reaching the target, the light source, from the start given different initial positions.

Result: The Eager Aggressor takes very less time compared to the Depressed Aggressor in reaching the goal from the start. The average time the Eager Aggressor takes to reach the goal state is approximately 3 to 5 minutes depending on the initial position. Whereas, the depressed aggressor takes around 50 to 60 minutes to reach the goal just once. In the meanwhile, the eager aggressor visits the goal multiple times.

# Conclusion

It could be concluded from the series of experiment that dynamic behaviours can be obtained from the Braitenberg vehicle on tweaking simple connections and providing with extra behaviours. The behaviour that emerge out of these robots are not very friendly. It is as if the robot is just thinking about oneself and doesn’t care for the rest of the world around. The behaviour showcased by the robots collectively are commonly selfish pushing each other around with no regards for the result. If the robots had a sense of what objects they are colliding with a distinction for other robots they might be able to behave in a friendlier way such as helping each other navigate. But, these robots have limited capabilities and sensing channels that they do not understand anything better than their current behavior. Increasing embodiment increases the level of perception of the robot. But, the usage of this perception is what makes the robot intelligent. That is why the Eager Aggressor wins in the last experiments.

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