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Robot navigation: implications from search strategies in exploring crayfish

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SUMMARY

Biomimetic applications play an important role in informing the field of robotics. One aspect is navigation – a skill automobile robots require to perform useful tasks. A sub-area of this is search strategies, e.g. for search and rescue, demining, exploring surfaces of other planets or as a default strategy when other navigation mechanisms fail. Despite that, only a few approaches have been made to transfer biological knowledge of search mechanisms on surfaces along the ground into biomimetic applications. To provide insight for robot navigation strategies, this study describes the paths a crayfish used to explore terrain. We tracked movement when different sets of sensory input were available. We then tested this algorithm with a computer model crayfish and concluded that the movement of *C. destructor* has a specialised walking strategy that could provide a suitable baseline algorithm for autonomous mobile robots during navigation.

KEYWORDS: Terrain classification; Search path; Autonomous robots; Navigation; Algorithms; Locomotion.

1. Introduction

In the last two decades, biomimetics has gained in significance for the field of robotics. The aim of biomimetics is to understand the principles found in nature and capture elements that can be transferred into artificial applications. Several different strategies for doing this have been developed. Some focus on mimicking the animal's appearance, e.g. cockroach,[1–2] snake,[3] earthworm,[4] scorpion.[5] Others study the sensory systems, e.g. flies,[6–8] bees,[9] moths,[10] cockroaches[11–12] and stick insects.[13] As a result, notable harmony has arisen between developers of new technologies and biologists: on one hand robots can be used to test hypotheses on animal control and behaviour, and conversely, biological systems lend themselves to solutions for technical problems. Stemming from this, a close appreciation of how biological systems work is advantageous in designing robust sensory-motor devices.[14]

Navigation, or elements of navigational processes, are central to any mobile robot operation. The task is divided into four stages: search, direction-following, aiming and guidance.[15] Search is the period where the robot moves but cannot detect its goal, thus there is no orientation towards a set point. It is considered as the simplest duty that navigation requires, but it also occupies the most time compared to other stages,[15] so it is a principal research area of navigation.

Only a few of the studies with biomimetic descriptions involving navigation algorithms concentrated on search mechanisms.[15–17] However, an effective search strategy is a skill any auto-mobile robot needs to be able to perform useful tasks.[18] For example, it plays an important role in autonomous robots in the fields of search and rescue,[19] demining[20–21] and exploring the surfaces of other planets.[22] In addition, a different search strategy can be applied as a backup if the main strategy fails,[15] for example when the robot built by Martinez *et al*.[23] could not find an odour plume that it was programmed to follow.

Animals can provide excellent models for developing suitable movement algorithms for robotic design. This is because searching is often essential for animal survival, e.g. when foraging, and due to natural selection fine tuning behaviour. It can be expected that some animals have very well developed and efficient search mechanisms. That is, in being efficient, they may be able to move in direct ways to reach a point in the quickest time or by covering the shortest distance. Different strategies are evident in a number of species. The soil-dwelling insect Collembolans, for example shows irregular walks and loops,[24] whereas the search paths of the turtle *Chrysemys picta* are linear.[25] Ants appear different again, using a pattern of ever increasing loops to search for their burrow after a foraging trip.[26]

Focusing on a specific animal system is a useful means by which to set clear targets for what the robot should achieve and provides a systematic framework to evaluate the success.[14] Examples overwhelmingly have focussed on the Arthropod group of animals, which includes insects, spiders and crustaceans. These species have segmented bodies, jointed limbs and a hard exoskeleton, features common to many mechanical robots so it is no surprise their behaviour and physiology has been important to biomimetics. Several studies investigate tracking odour plumes[29–32] and insect vision has provided a number of strategies that can be profitably applied for navigation in the air[6,9] and underwater.[10] While there is data on movement and navigation in those studies, there is less information about search strategies at ground-level, movement across a surface with no destination.

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Table I. The eight test conditions with different numbers of sensory input.

Experiment		Tank size	Light level	Explore medium	Extra stimulus	Goal
(1) *Normal exploration with no goal*	SDW	Small	Dark	Water		No
	SLW	Small	Light	Water	Vision	–
(2) *Exploration in an alternate environment with no goal*	SDA	Small	Dark	Air		No
	SLA	Small	Light	Air	Vision	–
(3) *Exploration with a goal (vibration source)*	SDWV	Small	Dark	Water	Vibration	Yes
	SLWV	Small	Light	Water	Vibration	Yes
(4) *Exploration in a large arena with no goal*	BDW	Big	Dark	Water		No
	BLW	Big	Light	Water	Vision	–

Crustaceans provide good biomimetic models to extend knowledge on movement and search patterns because they can move in relatively complex ways but this is controlled by a simple nervous system. The American lobster has been used intensively as a model for a biomimetic robot and a variety of different aspects have been incorporated, such as the outer appearance, neuronal control, myomorphic actuators,[16,27] sensors[16,28] and behaviours.[16–17,21] Crayfish, lobsters and crabs live in comparable habitats, so they show similarities, both biologically and neurologically. How species from these crustacean groups move has been analysed as the animals navigate towards odour plumes[29–32] (and see reviews[33–35]) and this has been applied to robots.[17,36] Ayers *et al.*[21] hypothesised that the behaviour found in lobsters is useful for application into robotics because the problem of demining requires solutions equivalent to those encountered in their natural biology.

Crayfish are emerging as potential animals to provide key information on search movements that may lend itself useful to biomimetics. They are explorers: similar in biology and lifestyle to lobsters, they move underwater, around all types of obstacles and terrain. The nueral servo control system and fan organs have been examined with the idea of application in robots.[37–38] A number of studies in the freshwater species, *Cherax destructor*, suggest that crayfish exploration and movement may also hold information central to robotics. The response of *C. destructor* when walking near walls, and walking with and without tactile input, are governed by the animals regularly making decisions or reacting to changing sensory input.[39–42] The success of this depends on continual adjustment and assessment even when no stimuli are present. Here we investigate the potential for the exploration behaviour of *C. destructor* to provide insight into efficient algorithms for automated robot movement. We tracked movement of a crayfish when different types of sensory input were present. We describe and model the paths and strategies used to explore terrain and discuss the findings with respect to implications for robotic navigation.

2. Observing Crayfish in their Terrain

To describe crayfish movement when different amounts of sensory input were available, stimuli in an experimental arena were systematically varied (Table I). The trials were designed to test a typical search phase of robot navigation, i.e. when no goal or target can be detected, as well as provide a comparison to some trials when a goal was present. Four sets of experiments were executed:

(1) *Normal exploration with no goal.* The normal condition trials were carried-out in darkness to remove visual information that may provide a 'goal' and therefore direct movement. In this environment the crayfish had only its own body movement through an unobstructed, unguided section of water.
(2) *Exploration in an alternate environment with no goal.* A different situation was provided by tracking crayfish walking in air. For crustaceans, walking can be different in and out of water[43] so it may be that any search strategy employed by *C. destructor* also differs.
(3) *Exploration with a goal (vibration source).* Hydromechanical information from a vibration source provided the crayfish with a potential goal to move towards or away from which could result in different search behaviour. This is a different goal source compared to the odour plumes used in previous research (e.g. refs. [29–32]).
(4) *Exploration in a large arena with no goal.* Crayfish were placed in a large arena to explore so that they could be tracked over a long distance allowing more data to be gathered.

Sighted tests were also included for all experiments to see to what extent an additional sensory input, vision, affects the search phase of crayfish movement. There were no obvious visual cues in the tanks but it may be that the walls or bottom or corners provide cues to guide animals, in which case behaviour could change. In all, eight different experimental configurations were used to test how movement changes when different types or amounts of stimuli were available. This included paths from 15 crayfish in each test configuration: SLW, SDW, SLA, SDA, SLWV, SDWV, BLW, BDW (tank size – Small or Big, light level – Light or Dark, exploration medium – Water or Air, extra stimulus – absent or Vibration, Table I).

The outer sides of the tank walls were sprayed with a white aerosol spray paint so external cues could not bias movement. The small tank was 80 × 60 × 50 cm (length × width × height) and the big tank 165 × 100 × 45 cm. White

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boards (acrylic or nylon), scratched to provide grip for the crayfish when walking, were placed on the bottom of both tanks. For treatments with vibrations a transparent plastic rod was attached to a vibrator (ADAK electronics) that was controlled by a stimulator (Grass). The stimulator was set so that the vibrator moved the rod back and forth, over a 3 cm distance, once every second. The rod was placed 5 cm from the centre of one of the end walls of the tank.

An animal was placed into a release enclosure in the centre of the tank. To control for any room effects the enclosure was directed so that the crayfish started randomly in one of four directions. Video recording (CCD camera, with infra red for dark filming, connected to Pioneer VHS video cassette recorder) was started after 5 min when the release chamber was removed by hand. For the vibrations, the stimulus apparatus was started 30 s before the enclosure was lifted to ensure that the water vibrations had dispersed throughout the tank. Recordings were stopped once the animal reached a tank wall. In four cases animals responded to the removal of the enclosure with a tailflick escape behaviour[44] and these trials were excluded from analysis because our focus was on walking motion. Tanks were drained, cleaned with a high-pressure hose and refilled with tap water to a depth of 10 cm to ensure any chemical cues were removed. This procedure was repeated after each trial in case of the small tank and after every fifth trial for the big tank.[39] Crayfish were only used once to prevent learning of the tank environment.

3. Movement Analysis

Video recordings were digitised to a PC using Let's Edit. Clips were converted with VirtualDub into uncompressed AVI files with a frame rate of 2 frames per second. AVI files (768 × 576 pixel resolution) were loaded into ImageJ and executed with the 'manual tracking' plugin (National Institutes of Health, USA – http://rsb.info.nih.gov/ij). Tracking was started when the enclosure was out of view. In each clip the tailfan (end of the crayfish) in the first frame and the rostrum (head) in every frame were tracked by positioning the programme's recording cursor over the respective point and clicking to accept the x and y coordinates (more detail in ImageJ help files). To prevent the paths being influenced by direct contact with one of the tank walls, tracking was stopped if the rostrum point came closer than 10 cm to a wall because our focus was on free movement and crayfish behaviour can be different near walls.[39–40] Data coordinates were pasted into Excel (Microsoft 2003) files for editing.

Data sets were standardised by translating the coordinates so the first rostrum point marked the origin and then rotating them so that the initial tailfan point was aligned with the negative y-axis (Fig. 1). The animals started from the enclosure with the rostrum point near the centre of the tank, within ±5cm each trial. Crayfish were tracked until they crossed a circular boundary, 10 cm radius in the small tank and 30 cm in the big.

To determine the effect of different numbers of sensory inputs the following parameters were extracted for all eight test conditions. *Time to start exploration* (s): the time from the first tracked frame to the frame when the crayfish started moving. *Pause time* (%): the percentage of time during the exploration, in which the animal did not move. *Velocity* (cm/s): the average of the distances between two tracked points (a 'step') moved per unit time (0.5 s) between the points. The calculation started when the crayfish began to move. *Index of Straightness* (*IS*): a measure of path shape, calculated by dividing the net displacement by the total distance travelled (sum of the lengths of each step, Fig. 1). Values close to one represent relatively straight paths, more sinuous paths approach to zero.[25,45] *Turning angle* (°/move): the absolute value of the signed angle between two consecutive vectors pointing from one rostrum point to the following one[24,26] (Fig. 1). *Heading angle* (°): the absolute value of the signed angle between the heading direction at the start and after a given net displacement distance (Fig. 1).

As the big tank provided a larger area, longer paths with a net displacement of 30 cm could be used for the analysis.

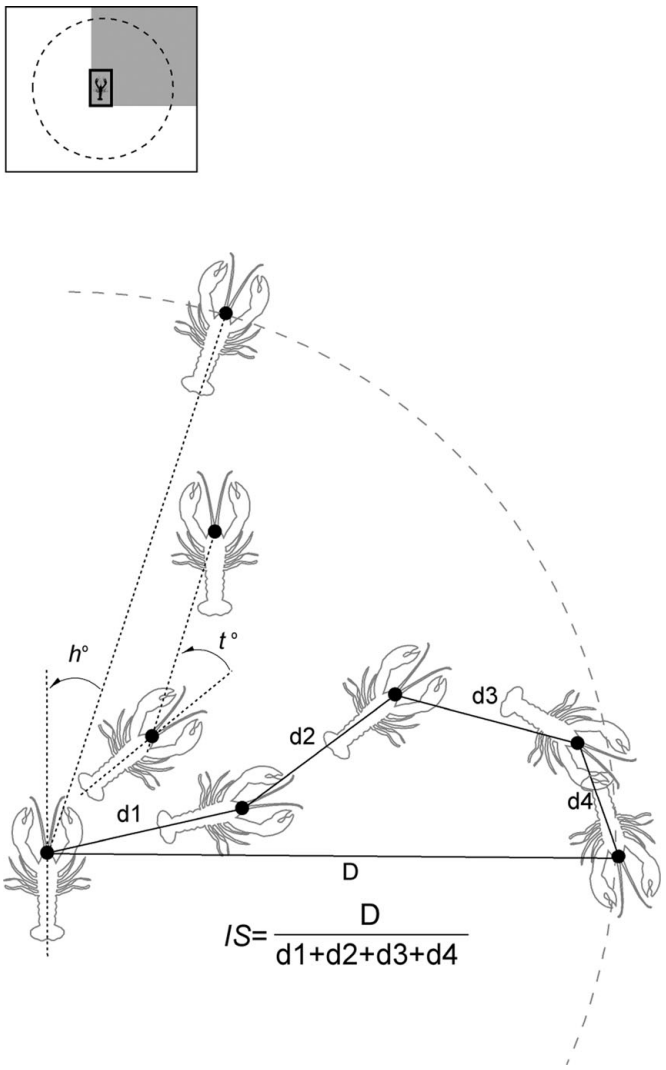


Fig. 1. Tracking the movement of *C. destructor*. Two paths are shown as a crayfish moves from the centre of the test arena to the outer boundary (10 cm and 30 cm radius for the small and big tanks respectively). Heading angle ($h°$) – the signed angle between the heading direction at the start and after a given distance. Turning angle ($t°$) – the signed angle between two consecutive vectors pointing from one rostrum point to the following one.[17,19] Index of straightness (*IS*) – net displacement (D) divided by the total distance travelled (sum of the lengths of each step $d1 + \cdots + dn$).

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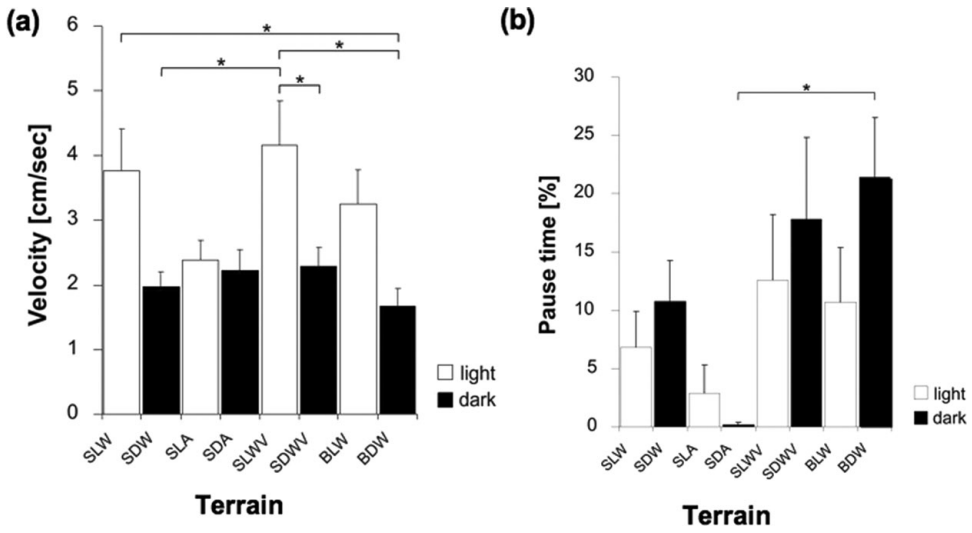


Fig. 2. Elements of the exploration of *C. destructor* that were affected by the number of sensory inputs available. (a) Velocity (mean + s.e.m.) of crayfish in each of the eight different treatments. Crayfish generally moved faster when light was part of the input. (b) Pause time (mean + s.e.m.) in relation to the total time since crayfish started moving. The * indicates a significant difference (Turkey's test $p < 0.05$; see text).

The following path descriptions were taken in addition to the previous measures. *Heading angle dependent on time*: the standardised coordinates of the rostrum points of each trial were plotted for 1, 2, 3 and 4 s after crayfish started to move. Time was only counted when the crayfish was moving. *Heading angle dependent on net displacement*: the standardised coordinates of the rostrum points of each trial were plotted for a net displacement of 5, 10, 20 and 30 cm. *Frequency distribution of turning angles*: the mean turning angles were summarised into 20° intervals and plotted as percentage of their occurrence.[24,45] *Net displacement compared with distance/time*: in the calculation a given net displacement value was compared to former ones. If this value appeared to be larger the crayfish moved further away related to the origin, if it was smaller it came closer. An arbitrary difference of 0.5 cm (2 pixel) between a given and all former net displacement values was defined. Animals having a greater difference were counted as 'coming closer'. This compromise allowed the animals having a pure rotation without being counted as coming closer. The net displacement/distance function illustrated the animal's net displacement related to the origin. An increasing slope meant the crayfish walked further away from the origin, while it came closer when the slope decreased.[26]

Statistics were used to determine if movement differed with the different stimuli and terrain. Data was tested for normality using a David test.[46] All data were normally distributed and so the parameters were analysed with one factor ANOVA in Systat software (VII Systat Inc.). Post Hoc Turkey's corrected tests compared data between treatments. The significant P-value level was set at 0.05. Means are reported with ± standard error of the mean unless otherwise noted. Additional explanations for some comparisons are provided in the text.

4. Description of Crayfish Movement

Different numbers of sensory inputs. Testing of the data revealed significant differences for velocity (one factor ANOVA $n = 15$, $F = 4.141$, $p < 0.001$) (Fig. 2a) and pause time (one factor ANOVA $n = 15$, $F = 2.604$, $p = 0.016$) between the different terrain conditions (Fig. 2b). Crayfish in the SLWV configuration were faster than those running SDW (Tukey's $F = 2.190$, $p = 0.015$), SDA (Tukey's $F = 1.942$, $p = 0.047$) and BDW trials (Tukey's $F = -2.489$, $p = 0.003$). The velocity of animals running in the latter experiment was also lower than the ones observed in SLW trials (Tukey's $F = -2.084$, $p = 0.024$). The test for the pause times demonstrated that significantly less pauses were made in the SDA than in the BDW trials (Tukey's $F = 21.173$, $p = 0.020$).

Altering the experiment configurations had no effect on the other parameters (Table II). In 65% of trials, resting was observed before heading off, in which case animals stood still for 0.5 s to 3 min and 47 s.

Getting underway. Crayfish generally travelled straight during the first four seconds of the exploration (Fig. 3). This movement was directed forward of the starting position in almost all cases with heading angles within −119° and 95° (BDW) and −102° and 86° (BLW). The mean time to reach the 30 cm boundary was 11 ± 2 s (BLW) and 17 ± 3 s (BDW) so this first four seconds of movement represents a short distance of about 10 cm for most crayfish (see inner 10 cm ring Fig. 4).

Long-term movement. Crayfish covered all directions of the terrain by the end of the exploration, 30cm from the origin (Fig. 4). The heading angles dependent on net displacement were −156° and 174° in the dark and −170° and 90° in the light trials. These angles were spread wider than in the initial movement close to the origin (Wilcoxon sign rank: $Z = 2.61$, $p < 0.01$).

Path analysis. The tracked movement produced characteristic path shapes. We counted the occurrence of single curves, straight, wiggly and other paths for each of the big tank experiments (Fig. 5a). The frequency distribution of the turning angles was symmetrical in both test conditions (Fig. 5b). Net displacement measured over time suggested

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Table II. Comparison of parameters for trials with different sensory inputs (one factor ANOVA, mean ± s.e.m.).

Parameter	F	P	SDW	SLW	SLA	SDA	SLWV	SDWV	BDW	BLW
Displacement angle (°)	0.085	0.999	53.77 ± 9.40	56.25 ± 8.83	59.24 ± 12.08	60.05 ± 12.30	62.27 ± 10.11	62.83 ± 9.61	60.76 ± 11.77	59.00 ± 8.34
Index of straightness	0.82	0.572	0.90 ± 0.02	0.93 ± 0.02	0.93 ± 0.02	0.90 ± 0.03	0.94 ± 0.01	0.90 ± 0.02	0.88 ± 0.02	0.92 ± 0.02
Start resting time (s)	0.579	0.772	5.4 ± 3.21	16.77 ± 7.95	25.07 ± 15.08	5.90 ± 2.79	11.47 ± 3.52	17.60 ± 12.50	15.77 ± 6.30	16.03 ± 8.48
Turning angle (°)	1.268	0.273	24.76 ± 2.58	17.52 ± 1.98	19.49 ± 1.69	20.22 ± 1.46	19.73 ± 1.93	20.75 ± 2.69	21.12 ± 1.64	17.53 ± 2.21

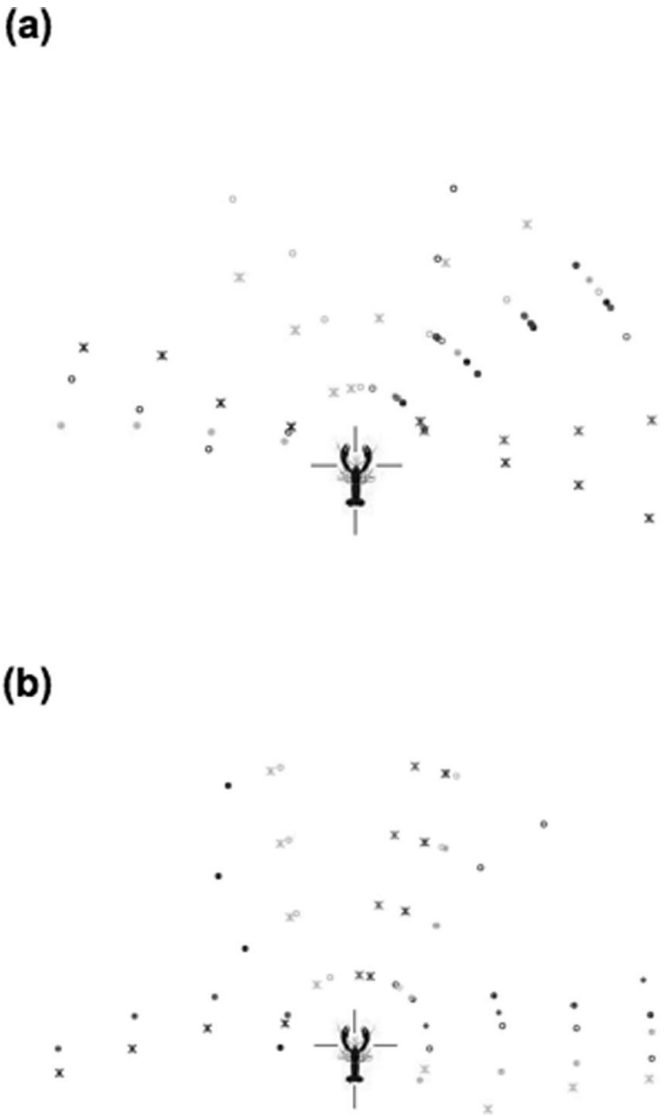


Fig. 3. The standardised position of the rostrum for crayfish after a moving time of 1, 2, 3 and 4 seconds from the inner to the outer circle, in the big tank (a) – BDW, (b) – BLW. Each crayfish is represented by the different symbols.

crayfish moved away from the origin in both test conditions in the big tank. Only 3 out of 30 animals spent more time coming towards to origin, as opposed to moving away.

5. Insights for Robotic Search Strategies from *C. Destructor's* Movement

The data suggest that *C. destructor* explores terrain with a characteristic strategy (Fig. 6):

(1) The number or type of sensory inputs are assessed, some of which can affect movement;
(2) Irrespective of speed and direction, movement is forward and straight at the beginning of the exploration;
(3) Movement is away from the origin;
(4) Movement is by select path types.

This strategy results in crayfish ending the exploration at random points around the boundary.

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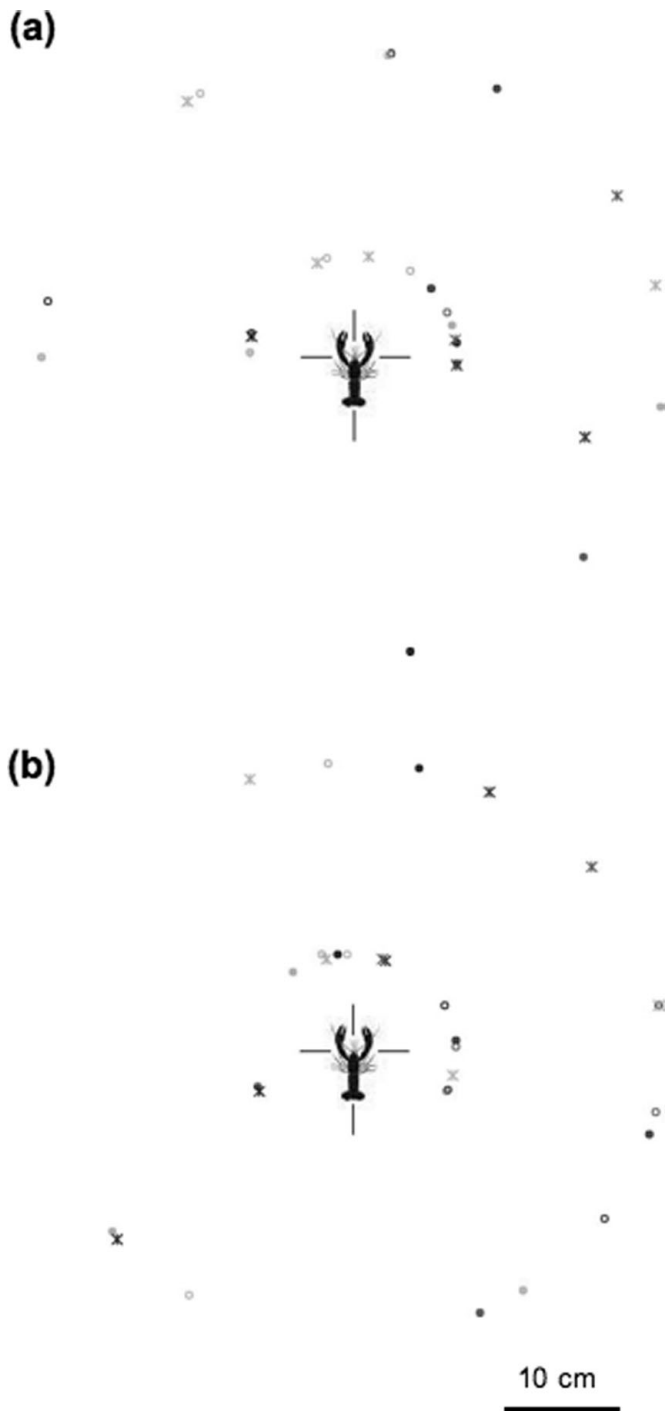


Fig. 4. Heading angles for a net displacement of 10 cm in the inner circle (start of exploration) and 30 cm in the outer circle (end of exploration). At the start of the exploration all headings were forward of the origin. When the boundary was reached, these headings had spread to anywhere around the boundary. Input combinations: (a) BDW big tank in the dark with water, and (b) BLW big tank in the light with water.

The only change in sensory condition that produced statistical significant difference occurred between light and dark sensory input. The statistical comparisons indicated that visual stimuli were the factor influencing the velocity the most. The only feature all significant slower trials had in common was that they all took place in dark conditions, whereas for their faster counterparts light was present. Wallace *et al.*[47] report similar observations for rats. Rats explore their environment in series of trips each consisting of the actual exploration period and the return to the point of release. By comparing the overall time for trips under dark and light conditions rats also move with a higher speed, when they can rely on visual information. Bell[45] claimed that animals use their best developed sensors for exploration. For a number of crayfish species, visual abilities are of some importance even though they are also active in darkness.[48–50] Thus, it can be expected that a given area can be scanned in less time when vision can be used for gathering information. Therefore, the speed during an exploration period can be increased without becoming less efficient.

For pause time only the comparison between the SDA and the BDW trial showed a significant difference. The second lowest value was found in the only other experiment tested in a tank without water. Even this trial was not significantly different to any other experiment. This supported the notion that moving in an unfamiliar medium can alter crustacean behaviour – movement in air instead of water was the most likely reason causing the observed variation in pause periods.

Some of the experiments had extra sensory input and a goal. There were some differences between these trials (see Fig. 2, Table II non-significant parameters). Velocity of the crayfish decreased in a number of the trials in the light compared to those in the dark (Fig. 2a). This difference remained whether there was a goal (the vibration) or the different environment (air), which suggests that the extra stimulus of visual input affects the movement and there is no difference in this species whether a goal or different environments are available. It may be that we did not observe a greater influence on path trajectories because *C. destructor* needed to be tracked over a greater distance, or they may respond differently to the nature of the goal, e.g. compared to odour plumes.

6. Computer Simulation of Search Algorithm

How crayfish moved during the exploration seemed to follow one of a group of set paths (straight lines, arcs, deep curves, wiggles or other random forms, Fig. 5b). It is possible that this diversity means the shape of paths is the result of a random search strategy. That is, because the distribution of turning angles was mainly clustered around 0° (Fig. 5a), *C. destructor* may have moved at a relatively fixed turning angle (e.g. about -10° to $+10^\circ$), but their behavioural output made slight deviations on this which produced the different paths. For example, the wiggly path is essentially several straight paths, each connected by a few large turning angles. Therefore it is possible that *C. destructor* may be exploring the terrain with the same 'programming', i.e. with the turning angle of every step based on the probability distribution in Fig. 5a, with direction mainly towards a 0° heading but larger turns would also periodically occur. From a robotics viewpoint this is an important issue because this becomes the main path of movement.

We tested this hypothesis, that *C. destructor* uses a random walk, by using a computer-generated model. This simulation

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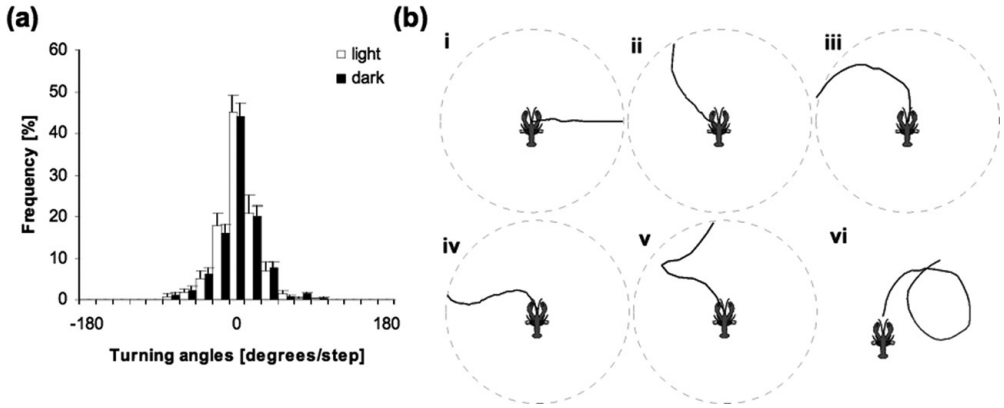


Fig. 5. (a) Frequency (+ s.e.m.) of turning angles of *C. destructor* from tests in the big tank. Most angles were between −10° and +10° degrees. (b) Path shapes that resulted from the turning angles shown in (a). Paths were grouped by blind observers to confirm each type: (i) straight, (ii) arc, (iii) curve, (iv) wiggle/zigzag, (v) ungrouped, (vi) loop. Note looping was only observed after tracking finished and path is approximated.

approach may seem less common in the field of biomimetics, but it still proves a valuable tool in current research environments.[13] Our simulation tested if a combination of mainly small turning angles, with a few larger angles, based on the natural turning distribution recorded earlier, could produce the observed paths.

6.1. Programming the computer crayfish

A spreadsheet programme was used to generate and graph the model data (Microsoft Excel 2003). Coordinates were systematically generated from formulae and then plotted to produce a path – the 'computer crayfish'. The computer crayfish started at the origin of a set of axis and was given coordinates (0,0). Step length for all moves was calculated in one column by a random value because the observed paths of crayfish in the big tank in the dark were different in length but in no consistent manner. Values were between 0 and 1 to scale to the plotting area. The turning angle was calculated from a look-up table that was based on probabilities from the distribution of turning angles recorded for crayfish in the big tank. There were 7 options: −60° (2% probability), −40° (5%), −20° (20%), 0° (46%), 20° (20%), 40° (5%), 0° (2%). This range covered the entire distribution and was sufficient to test the hypothesis, but this number of categories was a limitation of the software. From the turning angle, the heading as an angle between 0° and 360° was calculated and used to generate the next set of x and y coordinates in the spreadsheet.

The first five steps had separate formulae applied to replicate the starting movement of *C. destructor* we observed in the tanks. The initial heading was always forwards, i.e. positive y value coordinate angles between −90° and 90°. This was calculated from a second look-up table with seven options: −90° (2% probability), −60° (5%), −30° (20%), 0° (46%), 30° (20%), 60° (5%), 90° (2%) (Fig. 5a). The first five steps were in a straight direction, with a heading of 0° because crayfish in the tank initially started walking straight. In total, 40 steps were modelled, equivalent to the path lengths observed in *C. destructor* in the big tank experiment. We ran the model 30 times, the same as the number of crayfish used in the big tank experiments. In the output, we looked for similar shaped paths to those observed in the live crayfish – curves, loops, straight lines, arcs, wiggles. The simulated trials revealed that straight lines, arcs, wiggles and curves could be generated by the computerised crayfish (Fig. 7). Most common appeared to be unclassifiable paths that were not able to be placed into the groups of paths we observed from actual crayfish (Fig. 7a–d).

6.2. Comparison of the model with biological data

To determine if there were differences in the occurrence of simulated paths and actual walks, three human sorters were used. They were naïve to the experiment and asked to classify an unknown mixture of the real and simulated paths into groups they specified themselves (a total of 60 paths each, 30 from the big tank experiments and 30 simulated walks). While the sorters had some different names for their groups, there were four sets common to all the sorters and to our data: straight, wiggle, arc and curve. We then identified which paths in their groups were from the real and simulated walks. We analysed the sorters' groups to see if the random computer walk produced different numbers of each path type (Fig. 7e). The computer crayfish generated fewer straight and curve paths (straight: simulated 3.3 ± 1.5 mean $\pm$ SD, crayfish 8.3 ± 0.6; $n = 3$, $U = 0.000$, $p < 0.05$; curve: sim. 1.0 ± 0.0, cray. 7.0 ± 1.0; $n = 3$, $U = 0.000$, $p < 0.05$) and more wiggle patterns (sim. 7.0 ± 1, cray. 1.7 ± 0.6, $n = 3$, $U = 9.000$, $p < 0.05$). The occurrence of arcs was not significantly different (sim. 7.0 ± 3.6, cray. 9.7 ± 2.5; $n = 3$, $U = 2.000$, $p > 0.05$). Furthermore, computerised walks always ended forward of the starting point, unlike the real crayfish paths that often ended behind the starting point (Fig. 4).

Overall, the analysis between the observers and the simulated crayfish walks suggest that *C. destructor* use specialised strategies for efficient travel. These could be programmed in preference to a randomised walk for those robotic movements that require autonomous mobility across terrain (see Fig. 6). For this to be the case, we need to examine the natural paths in more detail and further develop our computer crayfish.

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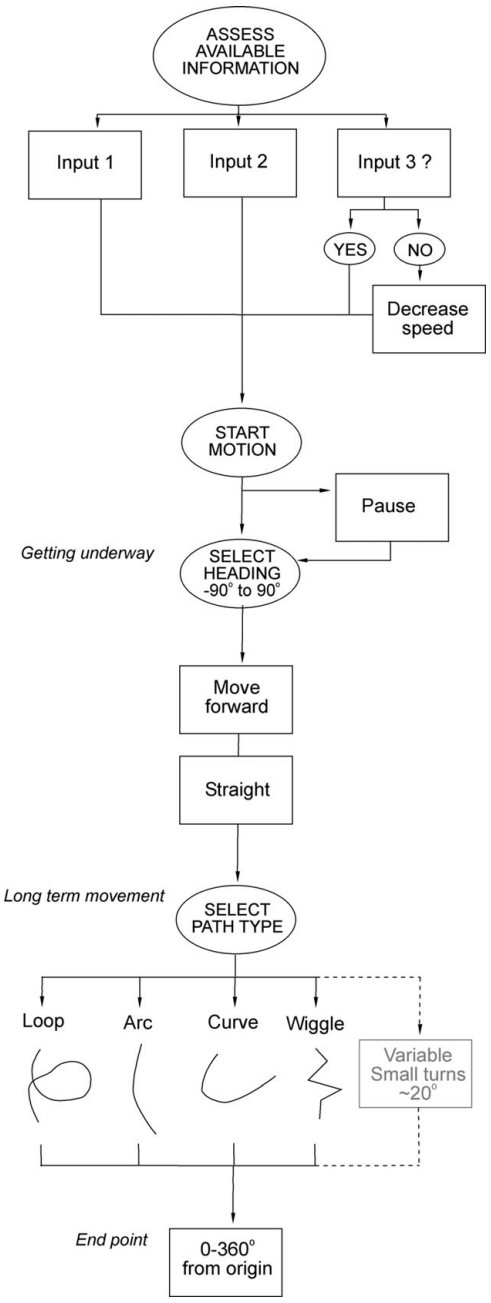


Fig. 6. Flow chart of the exploration algorithm from *C. destructor*. Input is assessed at the outset; two types were present in this test paradigm – ones that did not have an affect on movement (inputs 1 and 2), and one that did (input 3, e.g. light). Movement started in a forward, straight manner and then progressed to a characteristic path type. The computerised test path of variable small turns is shown by the dotted lines in grey. The end point was a location randomly distributed at the outer boundary of the test arena.

6.3. Extending the biological data of the computer crayfish

The model outcome suggested that *C. destructor* use different paths even when moving around with no detectable goal. To provide more detail on movement and make this result more applicable to robotic search patterns, we analysed the observed paths from *C. destructor* in the big tank experiments, grouping them according to their type (arc, curve, straight, wiggle). We focussed on turning angles and velocity as two major variables relevant to path analysis.[51–53] We plotted the distributions of turning angles and velocities in each crayfish's path, split into quarters of the exploration (Fig. 8). There was little difference in the distributions for the four sections of movement in the arc, curve and straight patterns (Fig. 8a–c). There was some variation in the wiggle path type but this was probably because only three animals used this strategy (Fig. 8d).

We performed Ward-Wolfowitz runs tests (Systat v12) to determine if the paths were correlated between each step a crayfish took when moving; that is, whether each step occurred in random sequence or whether the probability of a given step was the function of the outcome of a previous step. We did this for turning angles and velocities for each track of crayfish movement. In most cases, there was no correlation in successive turning angles, nor with velocities – $p < 0.05$ for 3 and 9 crayfish out of 30, respectively. While there were a few instances where crayfish paths were correlated with either turning angle or velocity, these were the minority and we conclude that, in general, for any of the path types we recorded, *C. destructor* moved without movements that were dependant on previous steps.

We compared between the four path types (arc, curve, straight, wiggle) and also between the four exploration segments within each type (0%–25%, 25%–50%, 50%–75%, 75%–100% of the exploration). There was no difference between path types for the parameters of velocity (ANOVA: $F_3 = 0.652$, $p = 0.589$) and turning angle (ANOVA: $F_3 = 2.134$, $p = 0.120$). We tested the data a second time to compare within each path type and used a Bonferroni correction to set the significance level at 0.025 for these tests. For turning angle, there was no difference detected between the segments of exploration for any of the path types (Friedman test: arc $p = 0.043$, curve: $p = 0.366$, straight: $p = 0.435$, wiggle: $p = 0.425$). There was also no difference in velocity between the four sections of movement in each path type (Friedman test: arc $p = 0.901$, curve: $p = 0.774$, straight: $p = 0.172$, wiggle: $p = 0.615$).

Given that there was little correlation between steps and no difference in velocity or turning angle, two important determinants in the outcome of path shape, begs the question why the computer crayfish was not more accurate at replicating the biological paths. Maybe there were aspects in the angle and velocity distributions that are important to programming but these were not significant from a statistical point of view. Therefore, we thought it valuable to adjust the computer crayfish so that it selected a path type and used the corresponding distributions for angle and velocity that we recorded in live crayfish and described above (Section 6.3). This did not however increase the accuracy of the computer crayfish (unpublished data). It may be that the paths were more correlated than the movement and our tests showed, or there may be subtle nuances in the exploration biology of *C. destructor* that our experiments did not reveal. Either way, further study will be required to reveal what parameters can provide additional input for the computer crayfish model.

7. Summary of Biological Navigation Strategies for Robots

There were six main findings from the biological strategy we observed in *C. destructor* that provide insight on the

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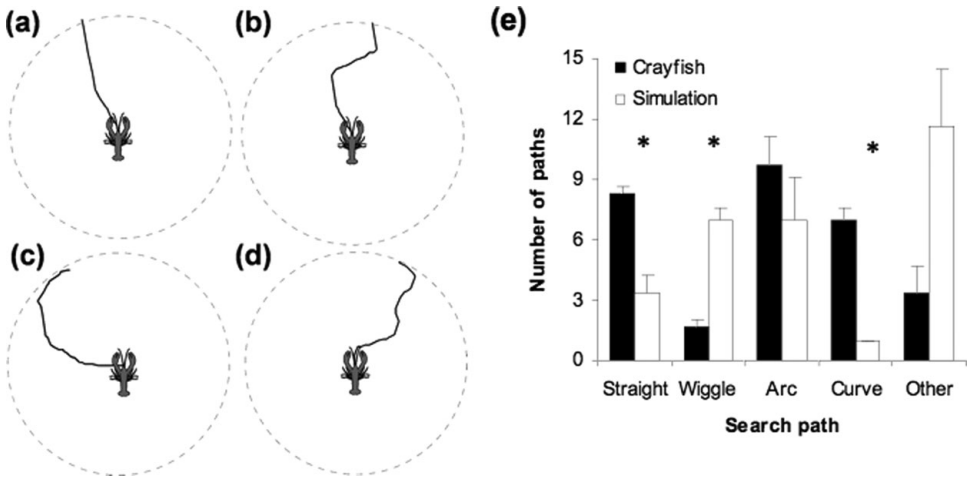


Fig. 7. Computer crayfish exploration suggested more complex movement than a simple random search strategy based on the trigonometric measurements that characterised the paths. A programme simulated the possibility of random movement as a search strategy in *C. destructor*. After 30 repetitions some of the paths observed in the test arena were apparent (a) – (d) but of different frequencies than as expected from the actual crayfish movement (e) (see main text).

suitability of crayfish as a model for robot navigation: (1) we were able to generate a computer crayfish model that required relatively little base information; (2) the computer crayfish was accurate with the live crayfish on some of the iterations of the model; (3) we were unable to fine-tune the computer crayfish with data collected from the study to produce an accurate output on all iterations; (4) the data was most informative to the start of a search; (5) there was no difference observed in movement when a vibration goal was present and (6) there was a difference when extra sensory input was available.

The search strategy of *C. destructor* described in this paper can be categorised according to other investigations made in biology. Bell[45] maintained that if no environmental cues were available, animals would follow one of four possible search strategies: random walk, straight walk, highly systematic strategies, kinaesthetic-input mapping or combinations and variations of these strategies. Kinaesthetic-input mapping was only used for homing animals and therefore not suitable for the trials investigated in this paper. In a random walk, the distribution of turning angles was uniform.[54] As the mean turning angles in all cases presented in this paper are concentrated around 0°, a purely random walk could also be excluded as a possible search strategy, as supported by our computerised crayfish.

One of the strategies is looping, which is evident in several species, such as insects,[24,55–56] birds[57] and mammals.[58] Looping occurs in response to an unknown or unsuitable environment,[24] comparable to the conditions for experiments in this paper. Although the paths presented here did not show loop patterns in the observation time, it could not be ruled out that crayfish might show similar patterns if observed for longer. The curve category of movement suggests these paths may be the start of loops if the crayfish had larger distances to travel. It was not feasible to test this in the present experiments because an unmanageably large tank would have been required. Further support of this is that one crayfish was observed to loop after measurements stopped being recorded for analysis (Fig. 5b–vi).

The movement patterns we describe provide most insight for the search stage of robot navigation. This navigational step often provides a back-up strategy when input sensors

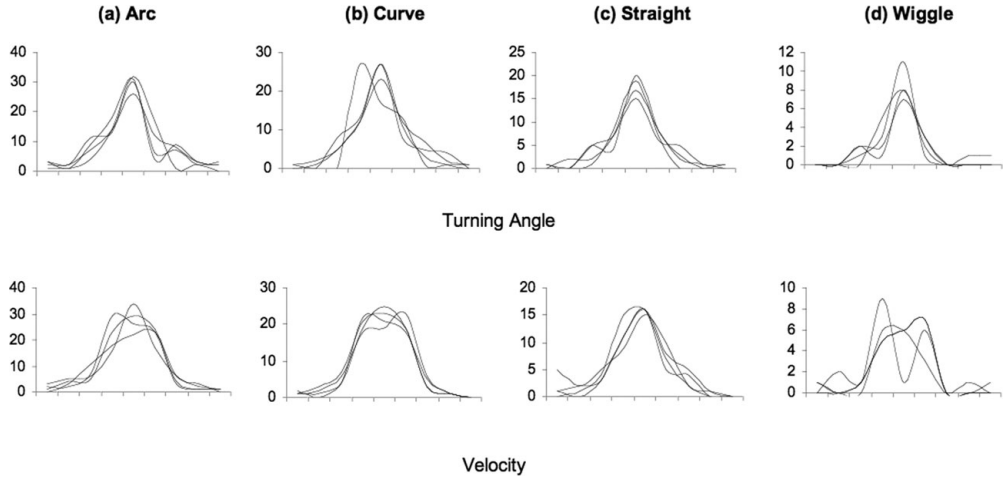


Fig. 8. Distribution of turning angles and velocity for the four path types – arc, curve, straight and wiggle. Each plot is has four distributions that represent the four quarters of the path that were analysed: 0%–25%, 25%–50%, 50%–75% and 75%–100% of the exploration.

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detect nothing, i.e. the robot cannot 'see' its goal. The data from *C. destructor* suggest that rather than programming a random movement in this situation, a pattern used in nature may be a more efficient alternative. We do not have sufficient information about the motivation behind the different patterns we observed from this study, but like a robot that is released to achieve a task, these crayfish usually wonder with a goal: to find food, shelter and mates. Most of our data represents the time when the animals are unable to detect their goal. It may be that the different patterns are pre-determined for a specific situation, or they also could be employed at random by the crayfish. Either way, movement when a goal cannot be detected is more complex than a random walk for this crayfish.

Biological systems are the product of evolutionary processes which can result in generation of inefficient mechanisms and therefore *C. destructor* could be considered to have less than ideal movement.[14] However, even if that were the case with the model presented here, we have data important to both the biology of the system and the robot technologies that might evolve from it and while the neural pathway was not examined here, the simplicity of the movement and formulae suggest application into technologies is a possibility, but we need further understanding of the biological nuances that affect the exploration of these animals.

8. Conclusion

By describing how *C. destructor* explores terrain, this study provided ideas for new search strategies in autonomous robotic design or ways in which to redesign existing ones for more efficient operation (e.g. those in review ref. [38]). Accuracy between the simulated output and the biological system was one we grappled with in our study and has been discussed as an issue in previous research.[59] We proposed that this was due to gaps in our knowledge about search patterns in *C. destructor*, a fact evident even in more thoroughly studied systems.[9] We were nonetheless able to reveal some of the manner in which crayfish navigate as they explore terrain. Adding data on *C. destructor* navigation and sensory processing near walls[39–42] could be one way to increase the value of this model system, particularly to extend it for the other stages of navigation, e.g. what happens when a goal is detected.

The sensory and control requirements of crayfish and robots share similarities, but this is limited by our ability to implement this in technologies. The computer crayfish model we described had a simple concept and testing this in the real environment would be a valuable step in the appreciation of the crayfish system for technological application. Decapod walking is already under development in some robots[21] and our data provide insight to further that technology. The natural crayfish system could, however, also lend itself useful in the search patterns of robots that use wheels or other devices to create movement – the strategy and goals of such robots are often the same.

Arthropod biology will continue to inform robotic technologies and crayfish biology remains as one of the potential sources, however as evidenced from this study, our investigations will need to continue to evolve in detail in order to reveal the full suite of natural behaviours so that models can be successfully generated. This may best be achieved with closer collaboration between biologists and engineers, with the aim to being more responsive to mutual needs and requirements.

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