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Towards Bio-Inspired Chromatic Behaviours in Surveillance Robots

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Abstract: The field of Robotics is ever growing at the same time as posing enormous challenges. Numerous works has been done in biologically inspired robotics emulating models, systems and elements of nature for the purpose of solving traditional robotics problems. Chromatic behaviours are abundant in nature across a variety of living species to achieve camouflage, signaling, and temperature regulation. The ability of these creatures to successfully blend in with their environment and communicate by changing their colour is the fundamental inspiration for our research work. In this paper, we present dwarf chameleon inspired chromatic behaviour in the context of an autonomous surveillance robot, "PACHONDHI". In our experiments, we successfully validated the ability of the robot to autonomously change its colour in relation to the terrain that it is traversing for maximizing detectability to friendly security agents and minimizing exposure to hostile agents, as well as to communicate with fellow cooperating robots.

Keywords: chromatic behaviour; bio-inspired robots; dwarf chameleons; camouflage; security robots

1. Introduction

The key for all the complex human problems is hiding in nature and we have to unearth it. If we traverse through the journey of natural evolution, we can come across plenty of evidence to the fact that living creatures have developed strong adaptive mechanisms and processes over millions of years, which offers a lot of potential for imitation into artificial models, systems and processes to solve our human problems. The enormous growth of a bio-inspired robotic field in recent times, is due to the technological inspiration it has acquired from the biological arena.

Robotic researchers were inspired by animal species such as huntsman spiders [1], dogs [2] and snakes [3]. As a result, highly efficient mechanisms, locomotion control sensing and autonomous behavioural strategies have arrived. The Cerebrunnus rechenburgi spider is mimicked [4] by a reconfigurable quadruped robot mechanism and a new energy based control approach has been presented which can crawl, roll and transform between the two states. For the purpose of evaluating control principles extracted from the cockroach, the design and simulation of a cockroach inspired hexapod robot is presented in [5]. The cockroach was chosen due to its remarkable running and climbing capabilities, and the widely available information on its biomechanics and control. Another study [6] presents a spinal cord model and its synthesis in an amphibious salamander inspired robot demonstrating how a primitive neural circuit used for swimming locomotion can be extended by phylogenetically more recent limb oscillatory centres to explain the ability of salamanders to switch between swimming and walking. A cricket, like a jumping mini robot, with a concept and design of a novel artificial hair receptor for the bio inspired sensing system of micro intelligent robots, is presented in [7]. The concept is derived from the natural hair receptor of animals, also known as cilium or filiform hair by several researchers, which is generally used as a vibration receptor or a flow detector by insects, mammals and fishes. A multi-robot architecture based on wolf packs is studied under different formations during pray hunting and predator avoidance is presented in [8]. The model has been developed and tested using the neural simulation language/abstract simulation language (NSL/ASL), mobile internet robotics (MIRO) systems and Sony artificial intelligence robot (AIBO) robots. In [9] the use of a biological behaviour found in many spices of birds to form lek is explored to guide the creation of groups of robots. As it demonstrates a group of individual entities forming around a scarce resource, it provides a sound basis for multi-robot formation.

Chromatism in living species, a process in which a species changes its body colour serves a wide range of purposes (viz); camouflage [10], an animal changes its colour to that of the environment; signaling [11], bodily colours are used for communicating information such as warning, sexual status and social interactions; and physical protection [12], an animal changes its bodily colour to safeguard itself from a harm due to an environmental or internal biological process. Cattle fish [13] realize dynamic camouflage by quickly acquiring visual information from the environment and neurally synthesizing appropriate skin colourations, Australian crab spiders [14] catch pollinating insects, such as honey bees on flowers, and can change their body colour between yellow and white. Many Chameleons, panther chameleons [15] in particular, have the ability to realize complex and dynamic colour changes during social interactions such as male contests or courtship. Male grasshoppers of the Kosciuscolatraistis species [16] in the Australian Alps immediately change from being dark that is almost black at low temperature, to a bright sky blue colour when exposed to warmth, which is a remarkable thermochromatic characteristic. The lizard, Anolis carolinensis [17], responds instantly to the colour of the environment by changing its skin colour to a bright green in the light and dark brown in the dark coloured environment. This change in colour involves Melanophore stimulating hormone from the pituitary gland. The Brachyurid species [18] have various colouration patterns that fluctuate among individuals due to behavioural interactions or a changing environment. In the fiddler crab, Ucapugilator, the historical notion is that colour change is regulated by circadian rhythms.

Synthesizing chromatic behaviour in robots remains as an untouched field for a longtime. A simple micro fluidic network that can change the colour, contrast, pattern, apparent shape, luminescence and surface temperature of soft machines for camouflage and display is studied in [19]. In [20], synthesis of facial colour expression using red Electro Luminance (EL) sheets for a humanoid robot heed to mimic social communication among humans is discussed. A novel system is proposed in [21] which expresses emotions for a robot by effectively changing the colour luminosity of its body using an LED luminous device. We elaborate in this paper, chromatic behaviours inspired from dwarf chameleons in the context of an autonomous surveillance robot, "PACHONDHI". The fact that this species can demonstrate its colour change response in relation to specific predators with varying visual capabilities, in addition to the colour of the terrain, has driven us to mimic dwarf chameleons. The ability of our developed robot to autonomously tailor the colour change in relation to the terrain in response to a pre-defined set of stimuli (viz) conspecifics and predators is established successfully in our experiments.

The espionages in urban areas are risky and tricky, particularly when entering buildings where no prior intelligence information is available. Current espionage missions involve sending out security personnel to specific locations, the use of fixed sensors and more recently the use of autonomous robotic vehicles to procure information. Equipped with imagery and maps of outdoor and indoor areas, a robot could autonomously estimate threat level, number of hostile agents and victims; conduct activity monitoring; track threats; and predict safer routes before human personnel could enter, avoiding any direct risk to humans [22]. We are, in our present research, attempting to expand the camouflaging capabilities of these robots, building upon our earlier work [23]. The capability of a surveillance robot to camouflage itself while on a mission and highlight its presence when being recovered—a characteristic that is critical for such security platforms—is established in the proposed design. Synthesizing chromatic behaviours in robots faces several challenges, such as the development of efficient approaches to colour generation, seamless integration of the same into a mobile robotic platform and the non-trivial process of implementing terrain and object recognition that acts as a trigger for the colour change.

A bag of visual words generated from speeded up robust features with a support vector machine classifier is used to achieve recognition of an object of interest whereas the terrain classification is achieved using a blob based detection algorithm. All these aspects are elaborated upon in this paper, concluding with experimental results using our "PACHONDHI" prototype fabricated in house with a minimum amount of off-the-shelf parts. The rest of this paper is structured as follows.

Section 2 presents a discussion about chromatic behaviours in dwarf chameleons and an extracted model for application in our robotic platform. The robotic architecture, "PACHONDHI", used for synthesizing and experimenting with the autonomous chromatic behaviours, inspired by the dwarf chameleon, is discussed in Section 3. Experiments and results validating the proposed research approach are described in Section 4. Finally, Section 5 concludes this study and discusses future scope.

2. Methods

Chromatic Behaviours in the Dwarf Chameleon

The chromatic behaviour in dwarf chameleons is the center of bio-inspirations on which this work is constructed. They are capable of changing their skin colouration and pattern through fusion of pink, blue, red, orange, green, light blue, turquoise, purple, brown and black [24]. By varying the wavelength of the light reflected off the guanine crystals that are present beneath a superficial layer under their skin, this colouration is synthesized [25]. The common reasons for the skin colouration in chameleons are the social signaling, camouflaging and temperature regulation. They often generate brighter colours when expressing aggressive behaviours and darker colours when they retreat or escape from a threat. This dwarf chameleon is native to the Cape Town region of the Western Cape Province in South Africa. The adult dwarf chameleon will grow over 15 cm in length including their tail. They are capable of rapid and significant skin colouration, saturation and pattern changes in response to physiological conditions and intentions. Several species of chameleons, and panther chameleons in particular, can rapidly change colour during social interactions. It was recently demonstrated that these colour changes are caused by the active tuning of lattice of intracellular guanine nanocrystals in specialized dermal cells called iridophores [26].

It is discussed in [27] whether dwarf chameleons show varying chromatic behaviours through colour change in response to multiple predators that use different perception mechanisms (snake and bird) to target prays. This study found that dwarf chameleons exhibited colour change behaviours in response to both predators taking on a brighter achromatically contrast colour in the presence of a snake compared to the bird, and also across a geographical context, background colouration and habitat morphologies. Further, they are also associated [28] with the use of colour change for social communication including male contests and courtships. They will maximize detectability to conspecifics while minimizing exposure to predators and this behaviour forms the centerpiece of our bio-inspiration model presented in this paper. The chromatic behaviour in the dwarf chameleon mainly involves eleven states: Roam, Classify_Species, Colour_Change_Contrast, Colour_Change_Camouflage, Approach, Colour_Change_Communicate, Classify_Intent, Pursue, Retreat, Hiding and Observe, as listed below as well as shown in Figure 1.

(a) Roam: It roams around looking for other species; if detected, "Species_Detected" condition is triggered to enable the "Classify_Species" state.
(b) Classify_Species: It classifies the detected species into either conspecifics or specific type of predators (Type I_Predator or Type II_Predator). If conspecifics "Recognized" condition is

triggered, the chameleon enables the "Approach" state to move immediately towards the conspecifics to attract attention. If "Type I_Predator recognized" is activated, then the chameleon switches to "Change_Colour_Camouflage" state. If "Type II_Predator recognized" is activated, then the chameleon switches to "Colour_Change_Contrast" state. At this juncture, another possibility is the activation of the "Species_Lost" condition which leads back to the "Roam" state.

(c) Approach: The chameleon starts approaching the conspecific to gain attention. If the "Conspecifics_Attention_Gained" condition is activated, then the Colour_Change_Communicate state is enabled whereas if the Conspecific_Uncertain is activated, then the chameleon switches back to the Classify_Species state.

(d) Colour_Change_Communicate: At this stage, the dwarf chameleon engages in social communication with the conspecifics using skin colouration. If the Colour_Response_Received from the interacting dwarf chameleon is activated, then the Classify_Intent state is enabled whereas if the Conspecific_Attention_Not_Gained is activated then the chameleon switches back to the Approach state.

(e) Classify_Intent: In this state, the chameleon classifies the detected intention based on the colour response received from the interacting chameleon. If the Intent_of_Interest_Recognized condition is triggered, the chameleon enables the Pursue state to immediately pursue towards the conspecifics. However, if the Intent_of_Uninterest_Recognized is activated then the chameleon enables the Retreat state. Else, if Colour_Response_Not_Received is activated then the chameleon switches back to the Colour_Change_Communicate state.

(f) Pursue: In this state, the chameleon moves actively towards the conspecifics. If the Species_Lost condition is activated, then the chameleon switches to the Roam state. Else if the Intent_Uncertain state is activated then the Classify_Intent state is enabled.

(g) Retreat: In this state, the chameleon falls back, moving away from the conspecifics. If the Species_Lost condition is activated, then the chameleon switches to the Roam state. Else, if the Intent_Uncertain state is activated then the Classify_Intent state is enabled.

(h) Colour_Change_Camouflage: To hide itself from the Type I_Predator, the chameleon alters its chromatophore functions to produce colours closer to that of the terrain it is traversing. If the Colour_Synthesized_Camouflage condition is activated, then the chameleon enables the Hiding state. Else, if the Type I_Predator_Uncertain condition is triggered, then the chameleon switches back to the Classify_Species state.

(i) Colour_Change_Contrast: To hide itself from the Type II_Predator, the chameleon varies the activity of different chromatophores in its layers of skin to produce contrasting colours in relation to its background. If the Colour_Synthesized_Contrast condition is activated, then the chameleon enables the Hiding state. Else, if the Type II_Predator_Uncertain condition is triggered, then the chameleon switches back to the Classify_Species state.

(j) Hiding: In this state, the dwarf chameleon goes into a passive static mode to escape from a predator with a synthesized skin colour in relation to the identified predator and background. If the Predator_Active condition is activated, then the Observe state is enabled. However, if the Colour_Not_Synthesized_Contrast is triggered then the chameleon goes back to the Colour_Change_Contrast state. Else, if the Colour_Not_Synthesized_Camouflage is triggered then the chameleon goes back to the Colour_Change_Camouflage state.

(k) Observe: In this state, the chameleon passively monitors the activity of the predator. If the Species_Lost condition is activated, then the chameleon goes to the Roam state. Else, if the Predator_Inactive condition is triggered, then the Hiding state is enabled.

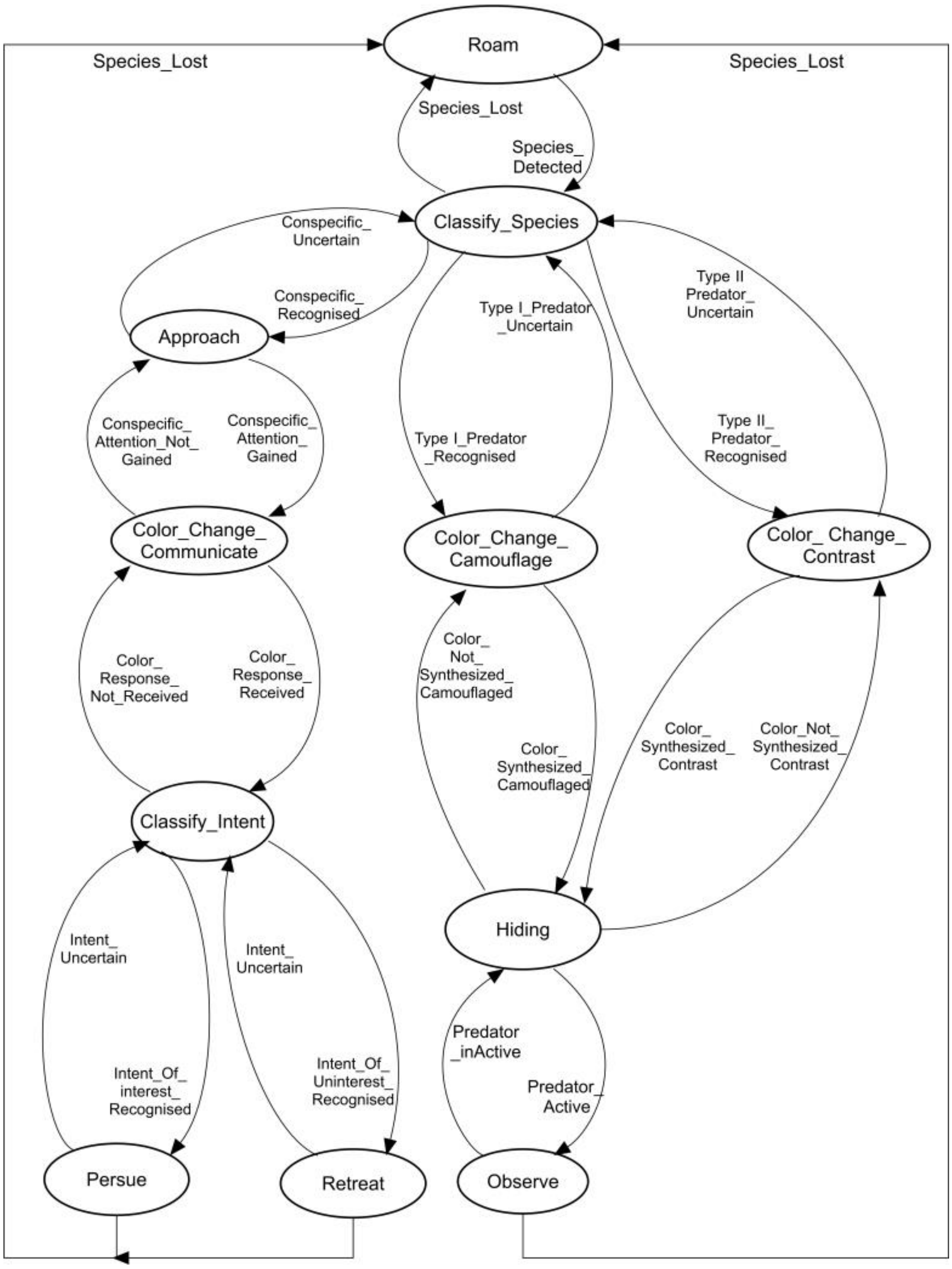


Figure 1. The eleven specific states involving chromatic behaviour of the Dwarf chameleon.

3. Design and "PACHONDHI" Robot Implementation

This section describes the "PACHONDHI" robot and its development, which has gone through many stages in the design of its mechanical structure, electronic control system and software architecture.

Robot Platform

The experimental robot platform is a rolling robot based on the principle of hemi-spherical wheels weighing about 800 g and has a smaller footprint of about 21.5 cm × 15 cm × 15 cm. This rolling mechanism is highly maneuverable, allowing robot to negotiate smaller obstacles, around objects and rubbles. Another key advantage of "PACHONDHI" is that it cannot be overturned. Figure 2, shows the physical design of "PACHONDHI".

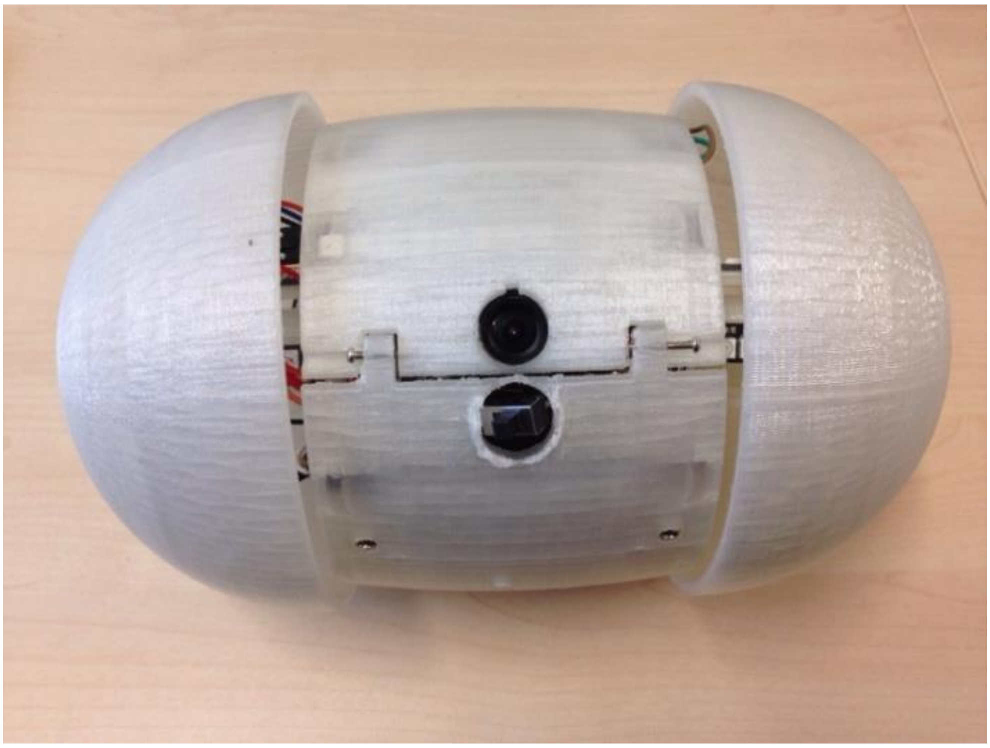


Figure 2. Second generation of the "PACHONDHI" robot prototype.

The mechanical design of "PACHONDHI" consists of two plastic half spheres and a central cylinder. The platform has a single central axle and uses two tiny brushed direct current (DC) gear motors from Pololu for driving the wheels, to realize acceleration, deceleration and steering. Controlling the two DC motors at different speed results in steering and by counter driving the motors, turning on the spot can be achieved. The central cylinder contains all of the electronics, batteries, camera and DC motors. It has three controllers for perception, behaviour and motor control.

The perception module is an integrated AiBall camera and its OpenCV based server module that is used in "PACHONDHI" to detect and classify events of interest and terrain of interest, concurrently. The output of perception module is a set of significant events linked to the detection of a friendly agent, hostile agent, fellow robot and terrain type being traversed. The behaviour control module is an Arduino Uno that holds the core responsibility for making the chromatic behavioural decisions and locomotion actions based on the significant events detected by the perception module. The behaviour controller sends appropriate locomotion actions such as turning right, moving straight etc. to the motor controller which, in turn, breaks it down into motors primitive to be sent to the motors. Also, the behaviour controller sends specific messages to the LED interface device for synthesizing the rapid colour change. Figure 3 shows the system level architecture specifications for "PACHONDHI".

Currently, the developed platform allows for two modes of control: autonomous and tele-operation. In the tele-operation mode, "PACHONDHI" can be remotely controlled using a notebook or smart phone using Bluetooth connectivity where a human operator controls both the locomotion and chromatic status of the robot guided by the visual streaming from the camera onboard the robot. In the autonomous mode, we implemented the dwarf chameleon model presented in Section 2 wherein "PACHONDHI" roams around a given area looking for friendly agents, hostile agents and/or fellow robots using only visual features.

Our approach to event recognition is based on object classification work presented in [29], and starts with the extraction of robust local features using the speed up robust feature (SURF) algorithm running on the OpenCV server while the images are captured by an AiBall camera running onboard the robot.

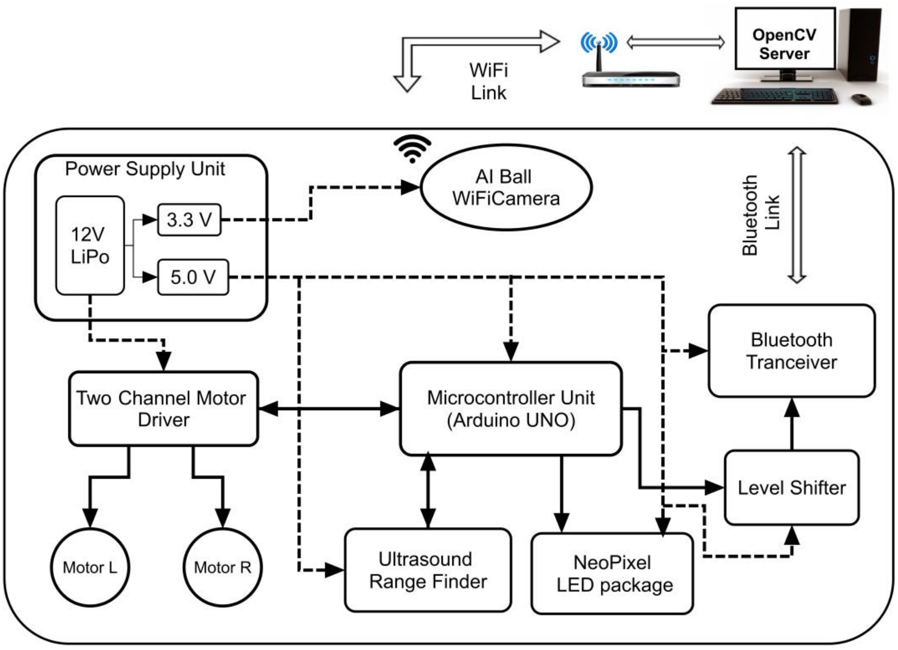


Figure 3. Control system architecture of the "PACHONDHI" robot.

The SURF algorithm uses Hessian matrix to detect key points. Given a point $u = (x, y)$ in a given image M, the Hessian matrix $H(u, \sigma)$ at point u and scale σ, is defined as follows,

$$H\ (u,\ \sigma) = \begin{pmatrix} L_{xx}\,(u,\sigma) & L_{xy}\,(u,\sigma) \\ L_{xy}\,(u,\sigma) & L_{yy}\,(u,\sigma) \end{pmatrix} \tag{1}$$

where, $L_{xx}\,(u,\sigma)$, $L_{yy}\,(u,\sigma)$ and $L_{xy}\,(u,\sigma)$ are the second derivatives of the image.

Once the key points and descriptors are extracted from the training set, then the descriptors are clustered into N centroids using a standard K-means, unsupervised, clustering algorithm. The extracted descriptors are then treated as a "Bag of Words". For a test image acquired during the robot run, the SURF algorithm is again used to extract the robust local features. Each descriptor is then synchronized to its equivalent visual word by finding the closest cluster centroid in the dictionary. A summary of the number of words for each test image is then passed to a support vector machine (SVM) based learning algorithm. SVM's non-linear decision surface is given in Equation (2).

$$\mathrm{b} + \sum_{i=1}^{N} (\alpha_i y_i\ K(x, x_i)) = 0 \tag{2}$$

where, the input to the SVM algorithm is the training data $\{(x_i, y_i)\}$ in which x_i, is the feature data and y_i, is the label either -1 or 1. We used Gaussian radial basis function (RBF) for our work presented in this paper due to its proven computation efficiency as compared to other variants of kernel function as given in Equation (3).

$$K\,(x, x_i) = e^{-\gamma\,||\,x - x_i\,||^2},\ \gamma > 0 \tag{3}$$

where, γ is the kernel parameter.

The feature vector coefficient weights α_i and b in the above equation are the solutions of a quadratic programming problem. For the recognition phase, a summary of the number of words for each test image is then passed to a SVM classifier to categorize the image by the event types depending on presence of a friendly agent, hostile agent and/or fellow robot. Once a friendly agent is detected, the platform changes to a contrast colour in relation to terrain being traversed whereas in the case of recognizing a fellow robot, the concerned robot starts approaching the conspecific equivalent until a visual response is sensed from the other side. Then, "PACHONDHI" analyzes the intent of the fellow robot and decides either to pursue or retreat. However, in the case of a hostile agent being detected "PACHONDHI" switches colour to camouflage itself in its terrain, stay put and observe until the hostile agent disappears. The developed vision approach allows for recognition and tracking of multiple distinct visual characteristics at the same time, an essential capability needed for "PACHONDHI" to classify a detected species as a friendly agent, hostile agent or fellow robot and simultaneously classify the terrain being traversed into one of the pre-defined terrain types and initiate actions to synthesize colour change. "PACHONDHI" is currently capable of recognizing and synthesizing eight colours through the use of ten NeoPixel stick LED arrays embedded into the central cylindrical body part of "PACHONDHI". Each array contains eight tiny smart Red Green Blue (RGB) LEDs onto a printed circuit board (PCB) with mounting holes and a chainable design.

4. Experiments and Results

In this paper, we present our chromatic behaviour experiments involving fellow robots, hostile and friendly agents using "PACHONDHI", a real robotic platform. We ran three sets of experiments in which static images of fellow robots, hostile and friendly agents are placed at a distance of 100 cm between them, with a test arena of about 6 m^2. This experiment contains three stages; the first stage involves "PACHONDHI" and its interaction with a hostile agent; the second stage involves "PACHONDHI" and its interaction with a friendly agent; and the final stage involves "PACHONDHI" and a fellow robot. We repeated the experiment thrice by changing the colour of the terrain. We controlled the light intensity level in the test arena to be between 500 and 700 lux. We used three different coloured carpeted floors for validating the dwarf chameleon inspired skin colouration in response to the event recognized and traversed terrain. During the experiments, we placed our robot "PACHONDHI" and three static images of a snake, hawk and fellow robot representing a hostile, friendly and conspecific agent where the robot was trained with a set of learning database involving 100 images each for snake, hawk and fellow robot for classification. All other obstacles were removed from the test arena. "PACHONDHI" assumes a sea shell white colour for its cylindrical body as an initial state. In our experiments, the skin colouration in "PACHONDHI" was validated using the colour similarity index DeltaE 2000 [30] that computes the colour difference between a sample colour and a reference colour using a factor of 0 to 100. A colour similarity index of 0 represents no change and a colour similarity index of 100 represents extreme difference in similarity between two compared colours.

4.1. Chromatic Behaviour Involving Predator Agent

At the initial stage, when "PACHONDHI" started looking for an event of interest (i.e.,) another species in its vicinity, its body colour is sea shell white. In Figure 4a–e, snapshots from the experiments are indicated where the different behaviour stages were captured where a hostile agent was involved. Initially the colour similarity index between the robot and its background had a mean value of 40, 59 and 68 with respect to three different terrain colours used in the experiment (Red, Green, Blue).

If an event of interest was detected (Figure 4b), from the images captured from the camera on board the "PACHONDHI" it was classified further as hostile, friendly or a fellow robot. A static image of a snake was the hostile agent used in this experiment and there was on obstacle in the test area. On recognizing a hostile agent, PACHNODHI analyzed the visual characteristics of the terrain being traversed and switched the colour of the body similar to that of the colour of its terrain to achieve a camouflaging effect, Figure 4c. Once the "PACHONDHI" synthesized skin colouration, the colour similarity index between the robot and its background was found to change to 11, 23 and 21 with respect to the three different terrain colours. "PANCHODHI", upon rapid colour change, remained camouflaged without any motion while visually tracking the hostile agent as in Figure 4d. When the hostile agent had left then "PACHONDHI" switched back to the roaming state where it wandered around the test arena looking for another species.

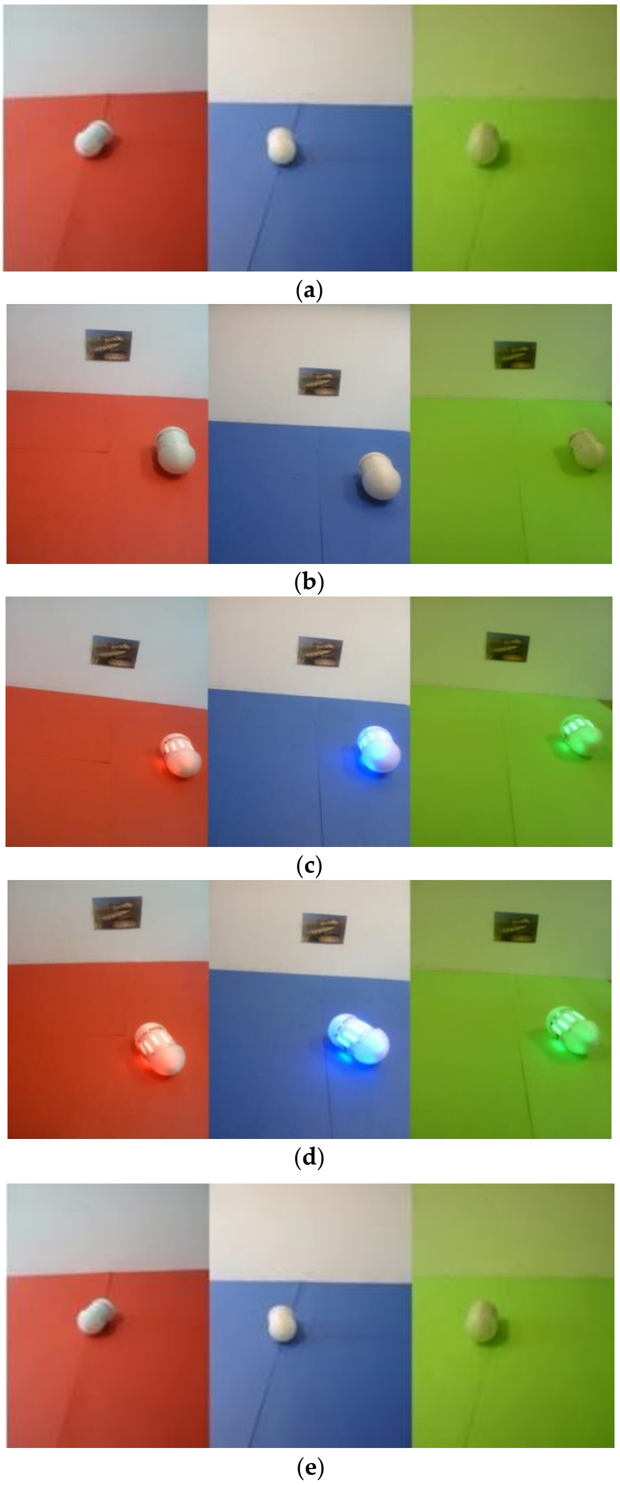
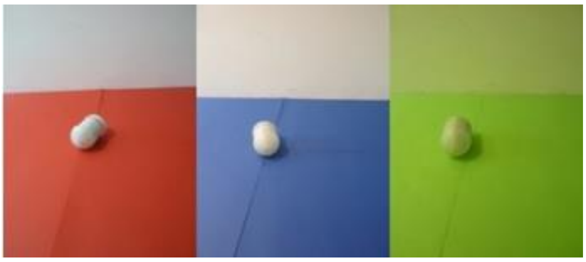


Figure 4. Chromatic behavioural changes of "PACHONDHI" where a hostile agent was involved with three different terrain colours. (**a**) Roaming; (**b**) Classify Species; (**c**) Colour Change Camouflage; (**d**) Hiding and Observe; (**e**) Roaming.

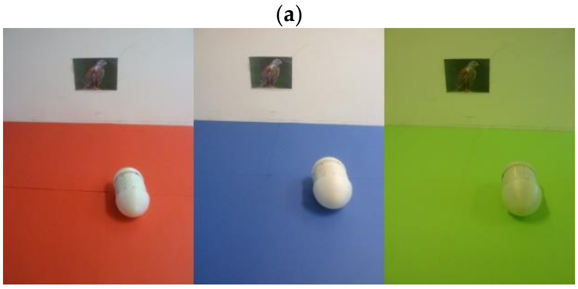
4.2. Chromatic Behaviour Involving a Friendly Agent

In the next stage of the experiment, "PANCHONDHI", was initiated with a roaming state with a colour similarity index of 40, 59 and 68 with respect to three different terrain colours experimented (Red, Green, Blue) and searching for an event of interest that was another agent. Snap shots from the experiments are shown in Figure 5a–e, where the different behaviour stages were captured in which a friendly agent was involved. On detecting a species from the images captured from the camera onboard the "PACHONDHI" as in Figure 5b, it was then further classified as a friendly, hostile or conspecific agent. The friendly agent was a static image of a hawk and there was no obstacle in the test arena. Once the friendly agent was recognized as shown in Figure 5c, then "PACHONDHI" analyzed the visual characteristics of the terrain in which it was traversing and switched the colour of its body to a contrasting colour to that of the carpeted terrain.

Once the "PACHONDHI" synthesized skin colouration, the colour similarity index between robot and the background was found to change to 97, 65 and 70 with respect to three terrain colours experimented, indicating extreme colour difference. Upon rapid colour change, "PACHONDHI" entered into the hiding state where it was highly observable to a friendly agent to be retrieved with ease as show in Figure 5d. If the friendly agent was lost or no action was taken to retrieve "PACHONDHI", then the robot returned back to the roaming mode searching for another friendly, hostile or conspecific agent.



(**a**)



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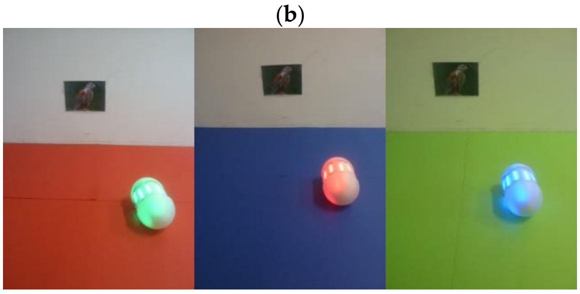

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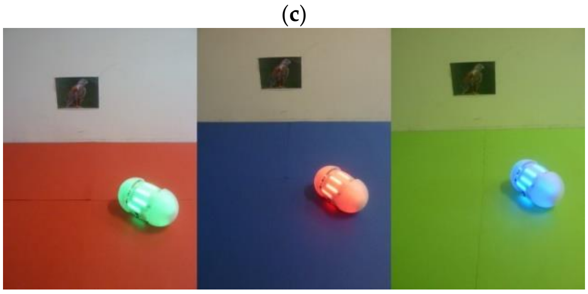
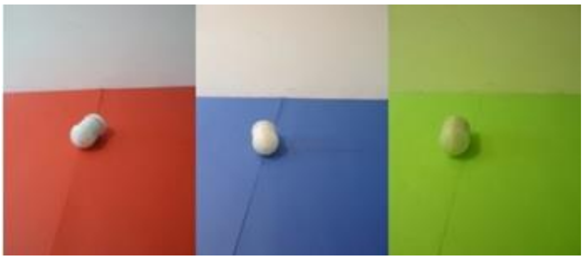


(**d**)

Figure 5. *Cont.*

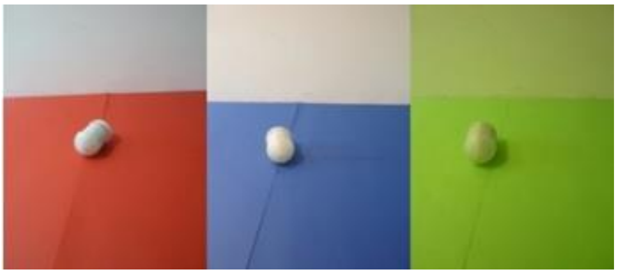


(**e**)

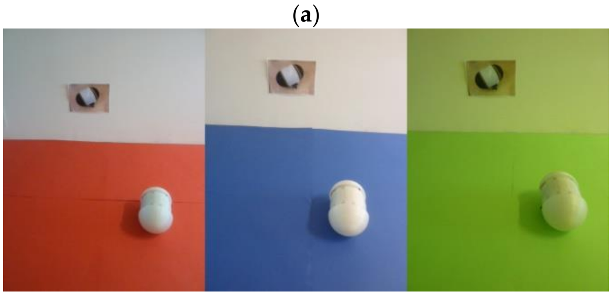
Figure 5. Chromatic behavioural changes of "PACHONDHI" where a friendly agent was involved with three different terrain colours. (**a**) Roaming; (**b**) Classify Species; (**c**) Colour Change Contrast; (**d**) Hiding and Observing; (**e**) Roaming.

4.3. Chromatic Behaviour Involving Conspecific Agent

"PACHONDHI", in the third stage, was again started with a roaming state with a colour similarity index of 40, 59 and 68 with respect to three different terrain colours (Red, Green, Blue). It begins actively searching for an event of interest (i.e.,) another agent. In Figure 6a–f, snapshots from the experiments are shown where the different behaviour stages were captured in the case of the involvement of a conspecific fellow robot. On detecting the species, as in Figure 6b from the images captured from the Camera on board the "PACHONDHI", it was classified further as a friendly, hostile or conspecific agent.



(**a**)



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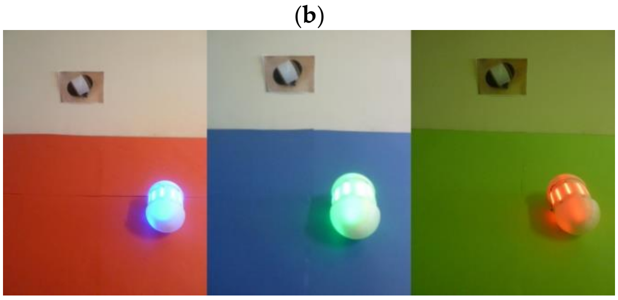
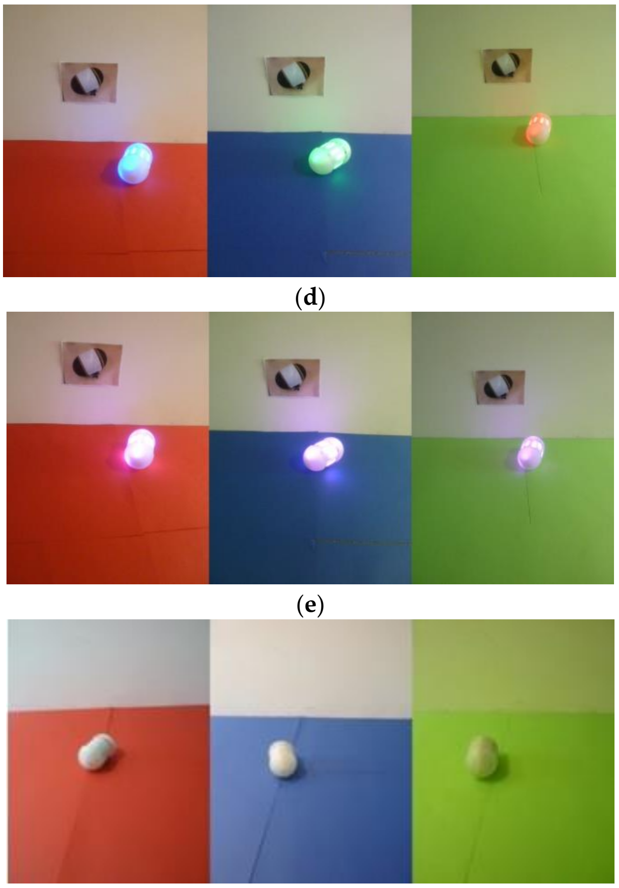


(**c**)

Figure 6. *Cont.*



(**d**)

(**e**)

(**f**)

Figure 6. Chromatic behavioural changes of "PACHONDHI" where a conspecific fellow robot was involved with three different terrain colours. (**a**) Roaming; (**b**) Classify Species; (**c**) Colour Changes to Communicate; (**d**) Approach and Pursue; (**e**) Approach and Retreat; (**f**) Roaming.

A static image of a similar looking hemi-spherical robot was used as the conspecific friendly robot and there was no obstacle in the test area. On recognizing the conspecific fellow robot, as in Figure 6c, the "PACHONDHI" analyzed the visual characteristics of the terrain being traversed and synthesized motion dazzle with a colour that achieved a colour similarity index of 50, 65 and 80 with respect to the three terrain colours. The motion dazzle effect was achieved through turning on and off the LED lights in order to gain the attention of the fellow robot.

"PACHONDHI", emanating with rapid colour change and synthesizing motion dazzle, approaches the conspecific fellow robot while tracking the latter as in Figure 6d. Once the conspecific robot noticed "PACHONDHI" and established communication, then "PACHONDHI" stops approaching and starts interacting with the former using skin colouration. If the "PACHONDHI" detects further interest in engaging the fellow robot, it maintains its skin colour as in Figure 6d. If "PACHONDHI" loses interest on the fellow robot, it will switch its skin colour to purple, indicating disinterest, and stop motion dazzle effects irrespective of the background colour as in Figure 6e.

In our experiments, we defined the sea shell white colour body of the fellow robot to indicate disinterest and during the experimental we ran the "PACHONDHI" synthesized purple colour, terminated its motion dazzle effects and moved away from the conspecific agent. When the fellow robot was lost, then the robot returns back to the roaming mode searching for another friendly, hostile or conspecific agent.

In Figure 7, the variation in colour similarity index between the robot and its traversing terrain during this phase is captured. The navigation trail of "PACHONDHI" captured during our experiment clearly shows the robot moving closer to the conspecific image pasted on the wall as in Figure 8.

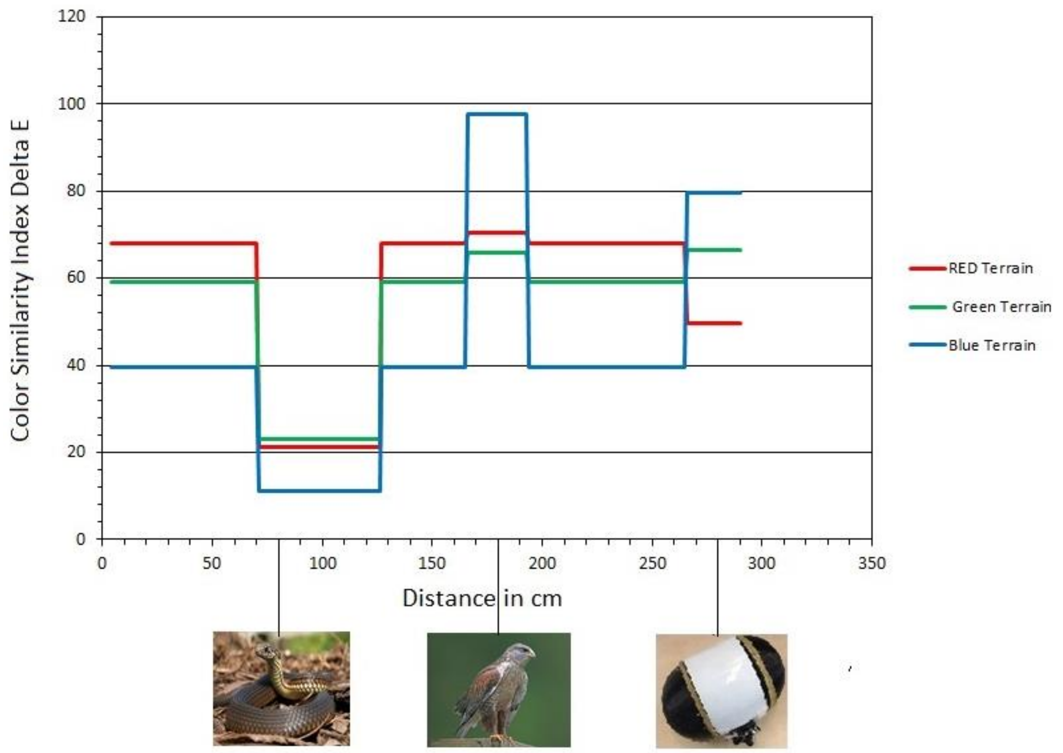


Figure 7. Colour similarity index plot with respect to terrain.

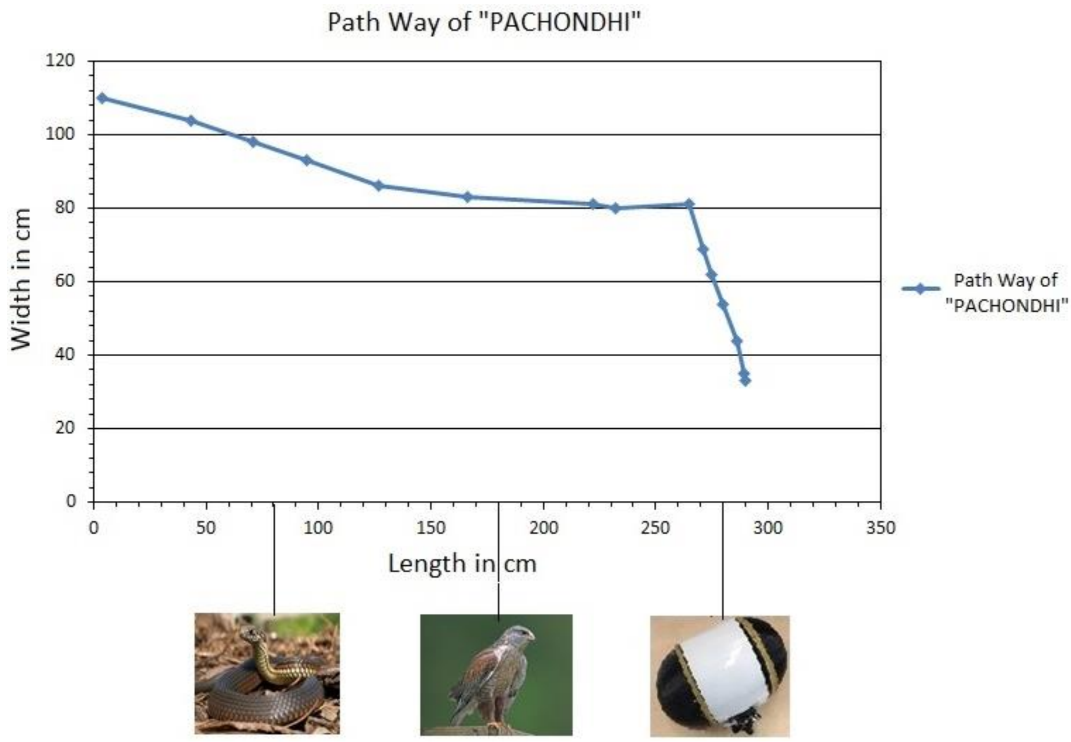


Figure 8. "PACHONDHI"'s navigation trail within the test arena.

5. Conclusions

The aim of this research is centered on bio-inspiration for synthesizing rapid colour changing behaviours for security robots. We developed a chromatic behaviour model deriving inspiration from colour changing behaviours found among dwarf chameleons. We experimented with the developed model with our surveillance robot, "PACHONDHI", capable of autonomously realizing rapid colour change using micro LED arrays embedded underneath its thin skin layer. The experiments conducted by us involved a fellow co-operating robot, hostile and friendly agents mimicking predators and conspecifics in nature. Through our experiments, the ability of the robot to automatically change its colour in relation to the terrain in which it is traversing for maximizing detectability to friendly security agents and minimizing exposure to hostile agents, as well as to communicate with fellow co-operating robots, is validated successfully.

Since the results presented in this work are done in a controlled laboratory set up, there are many factors, such as presence of more than one hostile and/or friendly agent, obstacle density, mobile agents, computational time and their navigating speed, visual perception limitations, among others, that create an impact on the behaviour results, which were not involved. In our future works, we also intend to include these factors in order to make the proposed behaviour model more realistic. Another scope for future work is to develop a set of design principles for synthesizing colour changing behaviours among security robots. Finally, we are developing an extension of the work presented in this paper to involve a team of co-operating robots that use only rapid colour change as a modality for communication to accomplish a defined task.

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