Butterfly Communication Strategies: A Prospect for Soft-Computing Techniques

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***Abstract*—This paper aims to show a new source of inspiration through Butterfly Communication Strategies to the field of Soft Computing. Inspirations and the algorithms that have been proposed already in this field have been surveyed and efforts have been put to provide the understanding of principal communication strategies of butterfly mating along with the different traits playing major role in it. The principal mating mechanisms were virtually shown with various experimental results using compatible software. The proposals were initiated from the observations to bring a collective movement or localization which could be one of the main aims in the field of soft computing.**

I. Introduction

The Earth is a habitat for many species living in diversity. Nature on this earth operates according to the laws of natural selection and survival of the fittest. Hence every inhabitant of this biological world strives to survive in its place undergoing some mechanisms through which it can feed, communicate, reproduce and defend itself. But unlike the human beings, other species use local natural resources and energy that are constantly cycled, reused and renewed. This is what attracted them, the property of being able to live in unison with the biosphere and not interfering with it. Hence they started mimicking the biological world to solve some of the problems in efficient ways. There are number of examples in nature which drew human's attention. Some of them are communication mechanisms, flying methods of birds, coloration & iridescence of insects, infrared communication of bats at night, honeycomb and spider's web buildings etc. Taking inspiration from them, he has been able to create many wonders artificially like flying machines, iridescent & stronger fabrics, complex structures & buildings, different kinds of robots, bullet trains etc. We can now understand that these bio-inspired inventions did really play a great role in human existence and there is still a great need to learn and mimic nature to acquire better living. This paper has surveyed different biological organisms which had inspired the humans to meta-heuristically use their behaviour in solving many engineering problems. Efforts have been put in taking inspiration from one of the well acquainted creatures, butterfly. As a part of this, the anatomy and the different communication strategies among butterflies were studied thoroughly along with their traits and the principal mating mechanisms have been simulated with experimental variations. Conclusive proposals were drawn for the future work.

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II. Literature Survey

With the growth in the fields of education and technology today, all the real-time practical systems have become non linear whose behaviour is non deterministic. The complexity here lies that we even don't have enough information about the problem itself due to its non linearity. For those type of computationally demanding problems, now a days, we choose soft computing which fulfils the requirements with less provided computation facilities. Soft computing refers to the field of computer science which is used for solving problems related to nonlinear and mathematically non-modelled systems and also for construction of new generation artificial intelligence. It differs from the conventional hard computing in the tolerance of imprecision, uncertainty and partial truth. Some of the Soft Computing techniques includes components like Neural Networks (NN), Fuzzy Logic (FL), Evolutionary Computation (EC), etc. Soft computing techniques generally resemble biological processes, and human brain is one of the main sources of inspiration. Very often, we come across problems where we need to find the best solution among all the possible ones, known as Optimization problems and many of the soft computing are used to solve these problems. There exists an another class of problems where we find not only the best solution but also some of the other possible solutions called Multimodal Optimization problems. A multimodal optimization problem can be well illustrated with respect to Unmanned Ground Vehicles (UGV). A group of UGVs works together and explores a highly complex area, locates targets and completes specified tasks with minimum complexity. In the literature, different means of control have been investigated and implemented for UGVs using soft computing techniques.

Of all the techniques of soft computing, evolutionary computation deals with the biologically inspired algorithms. Most of the biological species are social beings, i.e., these species have some self organized, decentralized control leading to excellent *emergent* behaviour that is not possible to be achieved by any organism alone but collectively. This collective behaviour is called Swarm behaviour. Seeley [1], Karaboga [2], observed that honey bees colonies have decentralised system to collect the food and can adjust searching pattern precisely in order to enhance the collection of nectar. Based on this, Karaboga and Ozturk [3], developed an Artificial Bee Colony (ABC) Optimization for solving multimodal and multi dimensional optimization problems and in real time, it was applied for Cluster Analysis problems. Marco Dorigo and Thomas Stutzle [4], observed that ants contain some pheromones called *Tail Pheromones* for creating paths from nest to food sources and vice-versa. By sensing pheromone trails foragers can follow the path to food discovered by other ants. This process of collective trail-laying and trail-following behaviour while travelling to food source and back to nest, has been considered as the inspiration. Hence a new algorithm called Ant Colony Optimization (ACO) was proposed to solve discrete optimization problems and it has solved Travelling Salesman Problem (TSP) successfully. Kennedy and Russell Eberhart [6], were interested in human and bird's social behaviour. They observed that, individuals interaction with one another while learning from their own experience, and gradually the population members move into better regions of the problem space. Also the study of Reynold's *Boids* [5], which is a simulated version of bird's flock model had helped them to develop Particle Swarm Optimization (PSO) algorithm. PSO targets to solve general continuous, discrete and also multimodal optimization problems. It was successfully used in optimizing the information content of the enhanced image with intensity transformation function [7]. Krishnanand and Ghose [8], were able to artificially depict the mating behaviour of glowworms to solve multimodal optimization problems. Every glowworm generates light using a chemical compound called *luciferin* and is attracted by other glowworm with high luciferin value, i.e., which glows brighter. Taking the above property and some features from ACO & PSO, they proposed Glowworm Swarm Optimization (GSO). This algorithm was tested on many multimodal functions and was used for Multiple Signal Source Localisation task, which is an identification of hazard sensing in ubiquitous environments by using a heterogeneous swarm of mobile robots known as Kin bots.

Many more algorithms found place in the field of Optimization based on the behaviour of bacteria, bats, honey bees etc. Now, this made us to think about finding a species of our interest which can inspire us and help in deducing a meta-heuristic process which is aimed to solve engineering problems in a more simplified way. "Our attention was then driven towards a little creature, moving swiftly, flashing its beauty and colourful wings. When studied deeply, we understood that the bizarre flights it takes do mean something and this made us to focus further on its behaviour and finally to this work. That little creature is nothing but the well known BUTTERFLY". The next section will briefly explain the biology behind the butterfly's life cycle before entering into the communication strategies of the butterfly.

III. Butterflies

Fig. 1. A White-Dragontail-Lamproptera-Butterfly

Butterflies communicate mostly for mating and their choice of mating is what attracted us. During the very small life span available, the things which a butterfly mostly does is feeding and searching for a mate. When you come across a butterfly freely moving in the garden, you never know, it might be busy patrolling or perching (ref. Sec. IV) for a suitable mate. Hence we would like to first introduce what a butterfly is, and its mating choices in detail. Butterflies belong to the order *Lepidoptera* [9]. In Greek, *Lepidos* means scales and *ptera* means wing. Lepidoptera is a very large group; there are more type of butterflies (about 28,000 butterfly species worldwide) and moths than there are of any other type of insects except beetles. Butterflies have large, often brightly coloured wings, and conspicuous fluttering flight. The life of butterfly starts with an egg hatched by a butterfly. The egg then turns into larva, then into pupa and finally a beautiful adult butterfly emerges out of pupa. The stage from an egg to a butterfly outcome (life cycle) is called *Metamorphosis*. Most adult butterflies live only a week or two, while a few species may live as long as 6-18 months. Female butterflies would always choose efficient mates to get higher nutrient values from them so that the inbreds would have good strength to live and to mate further. The choice of mate is done through communication among various butterflies. Next section explains various communication strategies along with their corresponding traits in detail.

IV. Communication strategies of Butterflies

Communication in butterflies is mainly for mating due to their short life span. Communication can also happen between the predator and the butterfly in which the butterfly tries to misguide the predator by camouflaging or hiding its bright colours. Below are the main mate locating behaviours of a butterfly and its defence mechanisms.

A. Patrolling :

In patrolling, the male butterflies are mobile and fly continuously in search of female butterflies until they find a female with acceptable colour and odour in their respective patrolling sites. In this, the male butterflies use UV light to recognize females of their own species based on UV reflections and wing patterns also. If females are closer in distance to males, males use an additional method of releasing pheromones for the female to sense. If that does not affect female, male further approaches female by butterfly dances and flushes pheromones to the female antennae. Patrolling species usually mate throughout the habitat at any time of the day, in high density conditions and where the habitat is large [22]. Patrolling may be beneficial in cold habitats where flight may attend as a heat gain approach. Patrolling is not constrained with respect to area of habitat hence it is non-territorial. In patrolling, the female must have to fly a certain distance to find the mate unlike perching where the male finds its mate. The species undergoing patrolling behaviour are Parnassius phoebus, Eucholes Ausonides, Hypayurotis Crysalus etc. [10].

B. Perching :

In perching, male butterflies are mostly immobile. They spend a long time sitting on the prominent leaf or hill top and survey the female butterflies passing by. The main attracting parameters are size and movement of the female butterfly [11]. Perching species usually mate during one part of a day in limited area of habitat, hence it is territorial and occurs in less density conditions. This is because perching males often return to a place near the previous site after investigating a passing female. The cost of territorial behaviour is perhaps less than that of patrolling because the territorial flights are shorter than the patrolling flights. The males in perching species have good ability to maneuver and accelerate; also they have higher body mass ratios, higher wing loadings and higher aspect ratios than patrolling species. When proper territorial sites are limited, males that have failed to achieve a territory adopt a patrolling strategy instead. This perching behaviour is observed in species like Hipparchia semele, Hypolimnas misippus, Aglais urticae etc [22].

C. Butterfly Defence Mechanisms :

Butterflies have various mechanisms to protect themselves from predation. Some species are camouflaged; they either look like something else, such as a leaf or stick, or blend in with their backgrounds. Others have patterns that make them appear to be a bigger animal, such as eye spots on wings[12]. The anatomy of a butterfly can be seen in Figure 2.

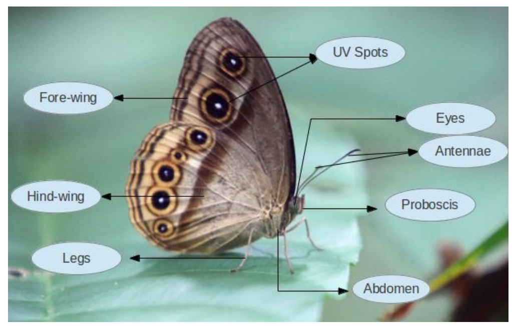


Fig. 2. Anatomy of a Butterfly

Monarch butterflies have an effective chemical defence, by being poisonous to predators. Many butterflies also use eye spots to ward off the predators. When a predator approaches the butterfly, it will suddenly show it's eye spots and frighten the predator away. Mimicry is a handy defensive mechanism for brightly coloured butterflies. Their colour patterns have evolved to appear like some of their foul-tasting relatives [13]. From the above, it is clear that a butterfly looks for certain traits in finding a mate and defending itself. Hence a brief description of few important traits is given below.

Important Traits in Mate Choice:

Pheromones: Butterflies use Hair Pencils to release a kind of scent called Pheromones. It is a strong attracting parameter and is released during courtship when the male fans or claps his wings and touches the antenna of the female butterfly. The olfactory receptors in the antenna of the female receive the pheromone as they have higher antenna sensitivity. These pheromones are also responsible for male-male competitions in defining their mating territories. Mate choice through pheromones is a close range response (less than a few meters), long distance pheromones is rare [14].

Butterfly size: In the early mating season, larger females mate with the larger males and smaller mate with the smaller males. Larger and symmetrical males are more attractive to females as the secretions produced by the male during courtship are proportional to its size.

This is found in Danus Plexippus, Monarchs etc [15]. In species like Bicyclus Anynana, normally sized males display higher mating than the ones with large hind wing and small fore-wing or vice-versa [16].

Movement (for refusal): Butterfly movements like fluttering are mostly observed during mate refusal behaviour. An already mated female resists the copulatory attempts by other males, for maximizing its oviposting (laying eggs) and feeding period [10]. The reluctance to mate is shown by opening its wing in a manner such that its dorsal side is exposed and abdomen is straightened. This area cannot reflect the UV radiation, resulting in the abrupt halt of male courtship behaviour. Fluttering, ascending flights, chemical signals etc, are also some of the mate refusing behaviours.

Colour: Colour of the butterfly can be either of the two possibilities; pigmented or structural colour. The structural colours due to the microscopic structures present on the lamella of the butterfly wings cause iridescence that is useful in communication [17]. As the light falls at different angles on the butterfly wings, iridescence causes the changes in colour for different angles of viewing. It is virtually in UV region but some species have a blue peaking iridescence. Iridescent coloration is also an intra-specific communication signal that flashes on and off during flight. Such bright flashes of colour could also be used as predator deterrent signals [18].

UV reflectance: UV reflectance in butterflies has special significance in mating signalling. The butterflies consist of series of marginal eye spots on both the dorsal and ventral wing. The eye spots on the ventral wings play a role in predator deflection and that on dorsal fore-wing play a role in sexual selection [19]. The female butterflies are also choosy towards the ones with the pupil of the eye spot visible it reflects UV light. However they prefer the mate with average sized pupil to the one with enlarged pupil size. The females can detect the differences between the males with varying UV pupil reflectance patterns and hence males with brighter pupils are more attractive. In some species like sulphur butterflies, male and female butterflies only differ in UV region; where the males being strongly UV reflective and the females non-reflective in UV [20].

Role of relative species density: Some species like Satyrine butterfly prefers low density conditions for mating, while the other species like Papilio Zelicaon prefers high density conditions. Some species prefer either of these two [11]. The presence of sibling species in a niche of a species can affect its mating success. In the sibling species of Leptidea sinapis and Leptidea juvernica, probability of mating is dependent on the relative species density but not on density of conspecific species. Females are not more inclined to assess male quality and are choosier under high con-specific male density conditions. Female mating success has a striking drop when hetero-specifics were present [21].

Mating efficiency: The life time of a butterfly is about 1-2 weeks. A female generally does not accept a mate until it is two days old because of pheromone releasing inefficiency in inbred butterflies. A female butterfly usually mates only once or a few times and re-mates only if the supply of secretions from the previous mating gets depleted. However a male can mate repeatedly. The fitness (strength) of a male increases when it copulates with a female which has not copulated before ex: - Heliconiuserato. The older butterflies like the inbred ones, show aversion towards mating because of the less secretions of pheromones. Only adult butterflies show better mating efficiency [22].

Vision: Butterflies have a vision of 360^o due to their compound eyes called as Omni-vision. Its range is about 1 cm to 200 meters. In omni-vision, the image a butterfly sees is in the form of mosaic [23]. It can also see the direction in which the electric field of a beam of light is oscillating (polarized light). Butterfly is extremely efficient at detecting movement but cannot focus its vision; hence what it sees is only a blur. Butterfly receptors can only perceive higher colour frequencies and hence are blind to red [17].

Migration - Choice in unfavourable conditions: During unfavourable conditions butterflies, mostly Monarchs (species), migrate from one place to another. An important difference with bird migration is that an individual butterfly usually migrates in one direction, while birds migrate back and forth multiple times within their life span[24]. The monarch migrates back and forth in a couple of generations. Butterflies navigate in several ways using landscapes, coastal lines, polarized light and earth's magnetic field [16] [25].

After studying in detail about the principal ways of different communication strategies viz patrolling, perching and defence mechanisms along with traits used, in the next section, the virtual behaviour of mate locating strategies is explained with the help of extensive simulated experiments.

V. Virtuality of Mating behaviour

The above section explained different mating mechanisms and corresponding traits thoroughly. In this section, we virtualize the natural behaviour of mating with some algorithmic assumptions for both males and females. All the simulations were done using Matlab R2012b (version 8.0) software.

A. Patrolling :

In patrolling (Ref. Sec. IV), all the butterflies are mobile. They are continuously in motion searching for their mates. The main trait the butterflies look for in their mates is the amount of UV reflectance and absorbance. Always the UV will be distributed to the females based on the distances in between them and the males. Extensive simulations were performed to check the patrolling mating mechanism with different variations in number of males and females and their corresponding velocities. All the simulations were performed according to the pseudo-code below.

Pseudo code

Randomly initialize male and female butterflies;
$\forall\ i$ (All males), set $UV_i = 10$;
Set maximum number of iterations $= iter\_max$;
Set $iter = 1$;
while $(iter \leq iter\_max)$ do:
{
    $\forall\ i, j$ do UV reflectance and absorption;
                    % using (1)
    for each female butterfly j do:
    {
        Select *mate*; % using $mate\ selection\ phase$
    }
    for each male butterfly i do:
    {
        Select *mate* and Update UV;
                    % using $mate\ selection\ phase$
    }
    $\forall\ i, j$ Update position;
    $iter = iter + 1$;
}

The random initialization of males and females in the work space is followed by the initial assignment of UV values to the males. Then the UV distribution phase is as follows: the males reflect their UV and the females receive them from the males based on the distances between them such that the nearest one receives more UV when compared to the farthest one, using the formula given in the Eqn.(1).

$$UV_{i \to j} = UV_i \times \frac{d_{ij}^{-1}}{\sum_k d_{ik}^{-1}} \tag{1}$$

where $k = 1, 2, \ldots, j, ., F; j = 1, 2, \ldots, F;$ F is number of female butterflies
$i = 1, 2, \ldots, M;$ M is number of male butterflies
$UV_{i \to j}$ is UV absorbed by j^{th} female from i^{th} male
d_{ik} is euclidean distance between i^{th} male and k^{th} female; d_{ij} is euclidean distance between i^{th} male and j^{th} female.

After the UV distribution and absorbance among the butterflies, the mate selection phase is as follows: female makes a choice among all the males and chooses the one from which it is receiving maximum amount of UV as its mate. Unlike the female, a male makes the choice only among those females which have chosen it as mate and selects one to which it is distributing maximum amount of UV. Suppose, if a male is not chosen as mate by any of the females in a iteration then it selects the female to which it is distributing maximum UV and updates its corresponding UV value so that chances of its selection as mate increases in the next iteration. After the mate selection phase, the movement phase is given by assigning velocities to both males and females such that in each iteration the butterflies move a distance of about one second duration.

TABLE I
PARAMETERS FOR DIFFERENT CASES IN PATROLLING

Case	No. of M	No. of F	Vel. of M	Vel. of F
Case1	15	15	0.2	0.1
Case2	5	70	0.05	0.05
Case3	70	5	0.15	0.15

Table I shows different parameters used for different case studies in patrolling. Below are the conclusions from the case 1. The above assumptions lead us to simulate the patrolling under three cases explained below:

Case 1: Number of males = Number of Females.

In this the simulations were run for equal number of males and females. Their number and corresponding velocities are shown in the Table 1. The Figure 3 shows the initial positions of the male (circle markers) and female (star markers) butterflies. The simulations were run until mating occured for every male and female. The path traversed by these butterflies along with their final positions (diamond spots) are also shown. We observe that more than 90% of pairs (one male & one female as shown in 'a') are formed. The exceptions are the groups of either one male & two females as shown in 'c'(happens when a female doesn't find any other male and it follows the best possible male in spite of its rejection) or one female & two males as shown in 'b' (This case happens when the female in the group 'b' selects a male but other male nearer to it, being unchosen increases its UV. This makes the female change its choice and choose the second male, however the first male now being unchosen increases its UV further. This process goes on and the female fails to choose one and hence pairs with both oscillating). The pairing of 'f1' and 'm1' is interesting. Initially, 'f1' chooses 'm3' but later at some iteration it chooses 'm2' because of UV. Mean while the male 'm1' being unchosen by any female increases its UV and manages to pair with the female 'f1' in spite of the competition from 'm2', 'm3'. No variation was observed even if the velocities of male and female were made different.

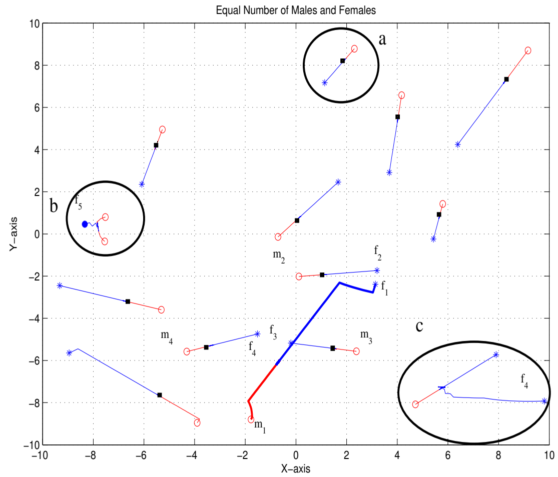
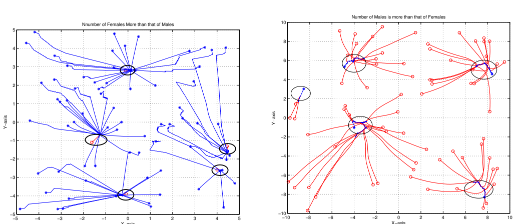


Fig. 3. Patrolling behaviour when number of males is equal to number of females

Case 2: Number of females > Number of males.

Here, simulations were carried out for small number of males against huge number of females but with same velocities. From the Figure 4.(a), localization of all females to the males forming localization points equal to the number of males is observed. The movement of males however was rather slow (see the encircled area in the Figure 4.(a)) when compared to that of females as each males is surrounded by many number of females and it need not search more for choosing a mate. This is also the thing which happens naturally, i.e., if a male butterfly has more number of suitable mates, it slows down its search. However if the assumptions are made such that there are male to male interactions, then it would give some useful experimental result. Similar to the case above, the differences in male and female velocities did not affect the result.



(a) Case-2 (b) Case-3

Fig. 4. Patrolling behaviour for unequal males and females

Case 3: Number of males > Number of females.

In this case, the number of males and females are considered such that less number of females are crowded by huge number of males with corresponding equal velocities. The result was same as that of the above case where all the males are localized to females and the number of localization points are equal to the number of females. Also the females in this case moved more distances (see the encircled areas in the Figure 4.(b)) when compared with the males in the previous case. This is because the mate selection of female is based on the UV reflected by the males to it and it changes for every iteration. In this case however when the velocity of females is made more than that of males, oscillatory nature was observed due to the reason that the males could not properly choose a female and the choice had to change for every iteration. The simulation of case 3 is shown in the Figure 4.(b).

B. Perching :

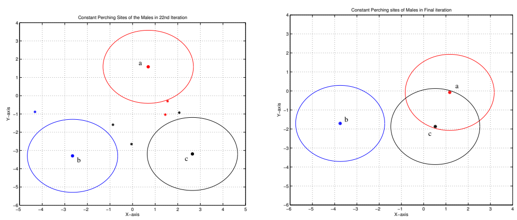
As mentioned in the section above, in perching, the male butterflies are almost immobile sitting on elevated positions and screening the females passing through. The main traits that are observed during the choice of mate are the size and movement (fluttering of wings) of the female butterfly. Each male defines its own perching site and searches for its suitable mate inside that boundary. A male butterfly mostly prefers a female of its own size. If two or more females compete for the same male, then the male chooses female based on movement. The male then selects the female with more fluttering velocity. Based on the above perching behaviour, the simulations were performed for constant and variable perching sites individually explained along with the observations. In both the cases, the number of females is more than that of males and is kept constant. The various parameters used for simulation are given in the Table II.

TABLE II
PARAMETERS FOR DIFFERENT CASES IN PERCHING

Parameters	Constant	Variable
No. of M	3	3
No. of F	10	10
Vel of F	0.5	0.5
Threshold	-	2
Radius update const.	-	0.3
Flutter Vel const.	2	2
Flutter Update const.	0.38	0.38

Case 1: Males with Constant Perching sites

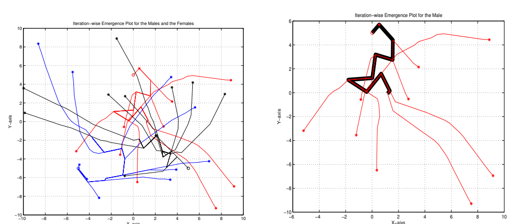
In this case, all the females are assigned with equal velocity and the male chooses the female based on similarity of size and directly takes a step and joins it, hence the perching site changes along with the male. However if two or more eligible females fall into its region, the male simply picks the one with more fluttering velocity. The rest of the same sized females are moved with a velocity towards the male (to the position before it replaces the chosen female) for one unit of time. The mated female remains with the male and moves along with it. The fluttering velocity is updated for unchosen females in the perching sites each time. In this way all the females of same size are collected by their corresponding male in every iteration and they form a group. Figure 5.(a) and (b) show the



(a) Iteration: 22 (b) Final iteration (26^{th})

Fig. 5. The Deployment of Constant perching sites of males at an iteration

positions of three males along with their perching sites at 22^{th} and final (26^{nd}) iterations. Here the males(a,b,c) are located at the centers of the circles(3 colours) represented with circle markers and females with star markers with the corresponding colours of males. After running the simulation we can observe that movement of each male through out the search space is very less. The Figure 6.(a) and (b) shows the emergence



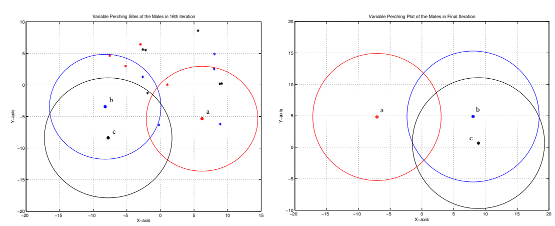
(a) For all males and females (b) One specific size male and corresponding females

Fig. 6. Emergence plot of both males and females at the end of simulation

plot of all the butterflies and extracted emergence of all butterflies belonging to one size. From both the Figures 5, 6 collectively we can observe that there was no interaction among males and females individually. However the males managed to collect all the females of their size and form a cluster. The highlighted line in the Figure 6.(b) shows the path traversed by one male alone and we can also observe the taxis behaviour of all corresponding sized females.

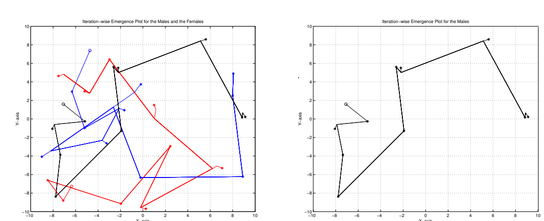
Case 2: Males with Variable Perching sites

In this case, initially all males are assigned with equal perching site areas and later as the iteration progresses, the site radius shrinks or expands based on the number (for threshold Ref. Table II) of female butterflies in it. The mate selection is based on size and fluttering velocity same as that of case 1 except that the unchosen females outside the perching sites are deprived of motion in this case, due to the reason that we are targeted to vary the perching sites for males so that the males collect the females by expanding or shrinking their domains in this process. We observe in Figure 7.(a) and (b), the various sized perching domains for all males at the 16^{th} and final(22^{nd}) iterations. Also Figure 8.(a), (b) shows the emergence plot of all butterflies and movement of one male butterfly along with taxis behaviour of corresponding sized females towards it. We observe that at final iteration, each male has managed to collect the females of its size. Variable perching site also resulted in better search space coverage than in constant perching site. Also the males share more mutual areas of perching when compared with case 1. Finally we have three groups, each with a male and its corresponding females.



(a) Iteration: 16 (b) Final iteration (22^{nd})

Fig. 7. The Deployment of Variable perching sites of males at an iteration



(a) For all males and females (b) One specific size male and corresponding females

Fig. 8. Emergence plot of both males and females at the end of simulation

VI. Future Works & Conclusions

In this paper, a new source of inspiration has been explored for the field of soft computing through different mating mechanisms in butterflies. Extensive survey has been done on various communication strategies in butterflies along with their traits. Later, the simulations were carried on to show the behaviour of principal mating mechanisms virtually. In all the simulations we aimed to mimic the basic behaviour of butterflies for various mechanisms by making some assumptions in their movement and we observed that in all the simulations, localization of search space is a common outcome. There are many variations in this exploration while mimicking the behaviour of patrolling and perching. The localization is limited due to the limited interaction among the agents. This can be improved by allowing the interactions among all butterflies by making modifications to the basic mating mechanisms, which ultimately increases the exploration of more search space and later can be used as a meta-heuristic butterfly model useful in solving many societal related problems.

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