Control of collective behaviours through artificial feedbacks

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Abstract

Lures and artefacts, which are almost as old as hunting and fishing, are used to elicit a particular behaviour in animals through key signals. The advances in robotics and sensors/actuators technologies opened the way to go from passive decoys to decoys able to fully interact with animals. Of special interest in this context are social species that are characterized by large networks of feedbacks of similar types but that involve various physicochemical vectors. The monitoring, the control and the breeding/farming of such populations often involve changes to the environment including artefacts that can be seen as environmental decoys. In this paper, we take the paradigmatic case of the formation of aggregates in a patchy environment : gregarious individuals having the choice to settle under an arbitrary number of shelters that are artificial agents able to communicate between themselves and to interact with the sheltered individuals through the modification of their abiotic factors such as temperature, light or odour. These systems can be modelled by the same generic models that serve as prediction and management tools. The model analysis allows to identify the behaviour of the artificial agents/shelters optimizing the population management.

Like luxury leather goods, Science hardly appreciates the counterfeits. For centuries – and long before scientists – hunters, fishermen and farmers have manipulated animal behaviour through the utilization of artefacts, such as fishing decoys, breeding mounts or scarecrows, in order to mimic another organism (conspecific, prey, predator) or elements of the (abiotic) environment. Nowadays, nest boxes or fish aggregating devices and artificial reefs are economically and/or environmentally important examples (Moreno et al., 2016) and arouse strong interest in many fields of science, including behavioural biology. The primary goal of such decoys or artefacts is to identify the key signals that elicit a reaction in animals. If for the "hobbyist" the best decoy is the one that best copies the original, for the biologist it will be a partial copy involving chemical, visual or acoustic characteristics of the animal. These tools were particularly popularized following the work of Tinbergen (1951), but biologists have seized upon them at the end of the 19th century, notably with the work of Plateau (1906) on bee-flower relationships. However, these artificial agents were passive, in the sense they induce animal reactions but do not respond to them and therefore these agents are not able to be involved in a behavioural sequence and to be integrated into a global dynamics.

The development of robotics and sensor/actuator technology opened new perspectives to integrate artificial reactive agents particularly in social systems that are characterized by many feedbacks (Camazine et al., 2003; Sumpter, 2010). In this perspective, gregarious and social arthropods should hold our attention, not only for their present and future economic importance but also because they show the most advanced forms of social integration with the eusocial species living in colonies (termites, ants, bees) that sometimes are described as superorganisms, or seen as decentralized biosensors or chemical mini-factories. Among the most widespread behaviours in social and eusocial species, gregariousness is the backbone of many social activities that may lead to e.g. collective choices or to the formation of spatial patterns. The dynamics of these processes are most often governed by a competition between positive feedbacks (e.g., chemical tracks in ants and termites (Czaczkes et al., 2015); dance in domestic bees (Seeley et al., 1991), silk communication in spiders or caterpillars (Krafft and Cookson, 2012; Fitzgerald, 1995; Costa, 2006)) which leads to an amplification and to a collective adoption of a given behaviour.

Various theoretical tools from physics and chemistry are at our disposal to identify the relationship between the behaviour of the individuals, their interactions and the emerging collective behaviour (e.g. genesis of rhythms, phase transitions, ...) (Camazine et al., 2003; Sumpter, 2010). In these settings, introducing artificial agents into a population or a society is, from a theoretical point of view, the mean to modify the global dynamics and to control the entire population (stabilize states, generate new instabilities) by generating new positive or negative feedbacks.

By taking the gregariousness as a biological model and using theoretical tools from complex systems, we will identify what types of artificial interactions must be introduced in the social system in order to achieve the objectives pursued by the manager or the experimentalist. The system studied is an environment in which on the one hand a population is distributed and on the other hand a set of sites on which individuals can aggregate and/or settle (Szopek et al., 2013). The proxy of these new interactions are “intelligent” sites (e.g. shelters) that are able to modify their physicochemical characteristics (and therefore their attractivity) depending on their own or respective levels of occupation (Bonnet et al., 2019). The differential equations describing the time evolution of the number of individuals on each site (X_i) is:

$$\frac{dX_i}{dt} = F\left(X_i, \rho_i\right) X_e - G\left(X_i, \rho_i\right) X_i \qquad i = 1, \cdots p \quad (1)$$

where X_e is the number of individuals exploring the environment; p is the number of sites, F and G are respectively the individual joining and leaving rate; and ρ_i are the biotic or abiotic parameters of the site i. The System (1) implies that that the individuals have not a global knowledge of the system: they only use local information and therefore they are not aware of the different sheltering options (e.g. Amé et al. (2006)).The synthesis of the literature and the analysis of eq.(1) reveal that all systems governed by these equations share the same dynamics and properties: e.g. they can exhibit multiple states or lead to the emergence of a consensus depending of the number of sites p, the population size and the parameters ρ_i. The analysis of eqs.(1) allows to identify the conditions for the emergence of a consensus (selection of one site). As it turns out, the minimal conditions to generate a consensus is $dF/dX_i \geq 0$ and/or $dG/dX_i \leq 0$, which correspond to the fact that sheltered individuals stimulate a conspecific to join the shelter and/or decrease the individual probability of leaving it (Nicolis et al., 2016; Calvo Martín et al., 2019).The minimal model is the one where the individual rate of joining (F) is independent of the population in the shelter and the rate of leaving (G) is a monotonically decreasing with a threshold :

$$G\left(X_i\right) = \frac{\theta}{1 + \left(X_i/k\right)^n} \quad (2)$$

The parameter θ is the component of the individual’s response to the shelter characteristics (ρ_i) such as temperature, light, *etc*. Other characteristics like humidity (Calvo Martín et al., 2019) may also affect the interattraction between individuals as expressed by the threshold k of sheltered population and the parameter n controlling the level of determinism of the individual response.

The introduction of artificial feedbacks into eqs.(1) would lead to a dependence of the parameters ρ_i characterizing the shelters or the sites on their level of occupation. These parameters would then become variables and two distinct cases can be formulated:

1. Each spot has only local information, on its own state of occupancy and can modulate it

$$\frac{d\rho_i}{dt} = U_i\left(X_i, \rho_i\right) \quad (3a)$$

2. or can communicate with other shelters (or with a master)

$$\frac{d\rho_i}{dt} = U_i\left(X_1, \cdots X_p, \rho_1, \cdots \rho_p\right) \quad (3b)$$

Two related questions are addressed with this theoretical framework: what are the basic mechanisms of the artificial agents (which can be shelters, feeding spots, *etc.*) modelled by the function U able (1) to prevent the natural emergence of a consensus; (2) to allow the formation of a consensus when the natural population is unable of it. Answering these questions goes through the modifications of the shelter characteristics and the objective is to identify the rules leading to the stabilization of a state or the emergence of new ones. In case (1) (case (2)), the objective is to stabilize (destabilize) the homogeneous distribution ($X_1 = \cdots = X_p$). The stabilization can be achieved by a local modulation of the the shelter characteristics (eq. (3)) which decrease the parameters θ and increase de parameter k of the equation (2). In the second case, the consensus can be obtained by reducing θ according to the occupancy level of each shelter. The study of the scripts where the shelters communicate with each other (eq. (3b)) shows that the cross-activation (cross-inhibition) between shelters stabilizes the homogeneous state (the consensus).

These questions are linked to the optimal management of the population such as the control of the individuals’ growth (by reducing competition or promoting cooperation between individuals) or the rapid adoption by a population of a particular behaviour. Maximizing the number of sheltered or feeding individuals in such a system could be trivially obtained by maximizing the number of aggregation/feeding sites but it would potentially lead under certain conditions to a dispersion of the population which would reduce the cooperation between individuals or the aggregation rate. *A contrario*, introducing the possibility of communication between artificial agents (corresponding to cross inhibitions between sites) leads to an optimal collective pattern.

Finally, the system defined by eqs. (1) can be easily extended to several populations/colonies that are in competition. Indeed, eqs. (1) consider a single population without recognition and conflict between individuals based on their origin as is the case with eusocial species where cooperation is intracolonial and competition is intercolonial (foraging). In this situation the objective pursued is the reduction of competition thanks to the desynchronization of the activities of the different populations generated by the artificial interactions (feedbacks) between colonies.

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