Flocking Approach to Spatial Configuration Control in Underwater Swarms

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Abstract: A modification of the flocking algorithm approach for a swarm of underwater vehicles is introduced. The proposed approach relaxes the symmetry of the inter vehicle interaction. It is thus possible to change the swarm spatial configuration assuming different formations with varying parameters. The swarm geometry is changed with a very limited effort, exploiting the capability of the flocking approach to make emerge a large scale arrangement. Examples of proposed variations are provided. The vehicles are dynamically modelled and the relative non holonomic proportional derivative controller is described. Experimental data are gathered from many vehicle physical simulations and graphically presented.

1 INTRODUCTION

Flocking is the behaviour exhibited by a large group of birds while flying or foraging. This genre of conduct can be found also among other animals: fishes perform shoaling or schooling, bees swarm, quadrupeds herd. Beginning with the seminal paper of Reynolds (Reynolds, 1987), many different authors have used this approach both to study animal collective behaviour and to try mimicking it using artificial entities such as robots (Ercan et al., 2010).

There are several results of formation control in underwater robotic swarms, see (Hou and Cheah, 2011) and references therein. The usually considered approaches can be classified in three major classes: behavior-based (Monteiro and Bicho, 2002), leader-following (Cowan et al., 2003) and virtual structure method (Kalantar and Zimmer, 2007) (Hou and Cheah, 2009). The artificial potential field is the usual tool exploited to control a large swarm of robots (Olfati-Saber, 2006).

The flocking approach in computer simulations relies on the computation of simple functions at the individual level. Each member of the group should not collide with its fellows (repulsive behaviour), should not loose contact with them (attractive behaviour) and should orient itself in the average direction of its neighbours (consensus term). It may exist an optional further term describing some kind of influence induced by the environment, typically an attractive potential (swarm goal) and/or a locally repulsive potential on objects (obstacle avoidance). With a variable implementation of these simple functions a flocking behaviour is set up.

A fundamental observation on these terms is their dependence on the inter element distance and not, for example, on direction, implying a radial symmetry. In the following a modification of this approach is proposed and investigated. The symmetrical constraint on the inter agent functions is relaxed. The introduction of some degree of asymmetry allows the possibility to obtain different spatial configurations for the swarm as a whole. Through the tuning of some parameters, it is possible to change the spatial arrangment of a swarm in some measure. This possibility may open the path towards several interesting applications.

In the second section the flocking basics and proposed variations will be put forward. In the third section the single vessel model and implementation employed in the experiments will be outlined. In the fourth section some experimental results will be shown. Finally in the fifth section the conclusions will be drawn and future direction of work outlined.

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2 THE FLOCKING ALGORITHM AND PROPOSED VARIATIONS

The basic recipe for a flocking algorithm is based on the distribution of the control input law among the single individuals, implemented as the sum of a given number of components. In (Olfati-Saber, 2006) these terms are three: a *inter vessel force* term, a *velocity consensus* term and a *navigational feedback* one.

$$u_i = f_i^f + f_i^v + f_i^n \tag{1}$$

The inter vessel force term accounts for the attractive and repulsive behaviour of the agents one against another and can be written as:

$$f_i^f = \sum_{i \neq j} \Phi(\| q_j - q_i \|)\mathbf{n}_{ij} \tag{2}$$

where q_j and q_i are the vessel positions and $\mathbf{n}_{ij}$ the unitary vector along the line connecting q_j to q_i. The argument of the Φ function is the Euclidean norm.

The velocity consensus term tells the vessel to orient itself towards the average direction of the neighbours. The navigational feedback renders the individuals *aware* of their environment (e.g. obstacle avoidance, swarm goal). With this latter it is also possible to set up a velocity consensus behaviour.
Once that these three terms are coded in the individuals the time evolution of the swarm elements produces a flocking conduct.

Let us consider the function in equation (2). It codes both a repulsive and an attractive behaviour. The average inter vehicle distance will depend of the function characteristics. In dynamical terms this is the force to be applied to the swarm element derived from a convex potential. The minimum in this potential is where no force is exerted on the agent and the equilibrium configuration is reached, this is linked to the parameters of the function. It is thus possible to control the average inter vehicle distance.

In the following the inter vessel force has been described by the function:

$$\Phi(r) = \begin{cases} -(\cos(\pi r/r_0) + 1), & 0 < r < r_0 \\ \cos(\pi r/r_0) + 1, & r_0 \leq r \leq 2r_0 \end{cases} \tag{3}$$

here r_0 is a parameter dependent on the average inter vehicle distance, its variation will change the swarm configuration from compact to diluted.

The force function expressed in equation (3) is here limited to the interval $[0, 2r_0]$, see figure 1, the main reasons for this are two. On one side it is possible to automatically introduce a cut-off distance on the visibility of agents (nearest neighbour interaction); on the other side this prevents that the contributions of all the many different vessels would result in a global potential affected by interference patterns which will disrupt the emergence of quasi regular swarm formation. Many different functions can be employed as soon as they show a repulsive and attractive behaviour. Lennard-Jones or Newtonian like potentials possess a singularity whenever the inter vehicle distance goes to zero. A physical vehicle cannot exert an infinite thrust to avoid collision, thus the here chosen function can implement a more realistic modelling, since it is limited, see equation (3). Naturally this may imply collisions among some vessels, due to the limited amount of thrust. Nonetheless through an opportune choice of r_0 the swarm density can be lowered to avoid such a dangerous situation.

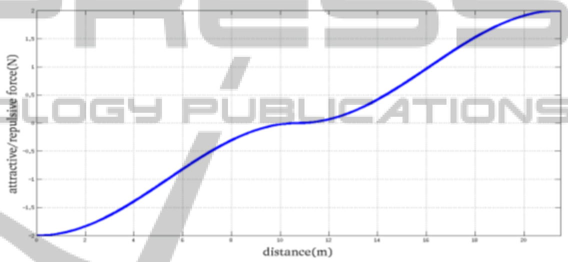

Figure 1: The $\Phi(r)$ of equation (3), a possible inter agent force, r_0 is in the inflection point.

An *ellipsoidal* distance is used to relax the radial symmetry implied by the Euclidean distance:

$$r = \sum_{i \neq j} \sqrt{\frac{(x_j - x_i)^2}{a^2} + \frac{(y_j - y_i)^2}{b^2} + \frac{(z_j - z_i)^2}{c^2}} \tag{4}$$

Through equation (4) it is possible to break the symmetry changing the three parameters *a*, *b* and *c* thus introducing further control on the swarm spatial distribution, in addition to that of its physical dimensions, as achievable with the tuning of the r_0 parameter in equation (3).

3 VESSEL MODEL

In the following a simplified vessel model is employed. Each vessel is sketched as a massive sphere that can be dynamically actuated through the application of a thrust along the *x* axis (the propeller) and can undergo two different torques: one around the *z* axis (yaw) and one around the *y* axis (pitch); no roll motion is considered.

If a group of N actuated underwater robots with six degrees of freedom is considered, their dynamics can be described as (Fossen, 1994):

$$\boldsymbol{M}_i\dot{\boldsymbol{v}}_i + \boldsymbol{C}_i(\boldsymbol{v}_i)\boldsymbol{v}_i + \boldsymbol{D}_i(\boldsymbol{v}_i)\boldsymbol{v}_i + \boldsymbol{g}_i(\boldsymbol{\eta}_i) = \boldsymbol{\tau}_i \quad (5)$$

where the subscript $i=1,...,N$ is relative to the single individual of the swarm, $\boldsymbol{\eta}_i$ and $\boldsymbol{v}_i$ are respectively the generalized coordinates expressed in earth fixed frame and the body fixed velocity; $\boldsymbol{M}_i$ is the inertia matrix, $\boldsymbol{C}_i$ is the matrix of Coriolis and centripetal terms, $\boldsymbol{D}_i$ represents the damping forces and $\boldsymbol{\tau}_i$ denotes the generalized forces supplied by the actuators. Inertial and Coriolis matrices take into account the added mass terms (Fossen and Fjellstad, 1995).

The flocking model produces the desired force $\boldsymbol{u}_i$ to be exerted onto each vessel in order to obtain a flocking behaviour. The low level robot controller is a proportional derivative controller proposed in (Hou and Cheah, 2011):

$$\boldsymbol{\tau}_i = -\boldsymbol{K}_p J_i^T(\boldsymbol{\eta}_i)\boldsymbol{u}_i - \boldsymbol{K}_d\boldsymbol{v}_i \quad (6)$$

where $\boldsymbol{J}_i^T(\boldsymbol{\eta}_i)$ represent the transformation between the earth fixed and the body fixed frames. In this work $\boldsymbol{K}_p$ and $\boldsymbol{K}_d$ are positive matrices which are not unconstrained, as in (Hou and Cheah, 2011), but have been written in order to consider the non-holonomicity of the vehicle, capable of limited actuation, i.e. a thrust and two torques. In more detail:

$$\mathbf{K_p} = \begin{pmatrix} k_p & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -k_p \\ 0 & k_p & 0 \end{pmatrix} \quad \mathbf{K_d} = \begin{pmatrix} k_d & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & k_d & 0 \\ 0 & 0 & 0 & 0 & 0 & k_d \end{pmatrix} \quad (7)$$

Furthermore the vessels are considered neutral, i.e. the gravitational pull and the buoyancy are assumed balanced.

Such a model is clearly simplified as confronted with a full model taking into account all of the underwater vehicle characteristics, nonetheless is capable of capturing the fundamental features of a vessel, allowing for an effective and physically plausible implementation.

All of the simulations have been performed in the Gazebo robotic simulator (Gazebo, 2012), which is an Open Source software package that computes all the dynamical aspects of the simulation, with the possibility of a graphical rendering of the results.

4 EXPERIMENTAL RESULTS

In the following some experimental results are presented. They are relative to two main sets of experiments: the inter vessel distance control and the formation emergence and evolution.

In all the experiments the swarm vehicles implement a velocity consensus function through a navigational feedback, i.e. an attractive potential pulling each vessel towards the x direction is operating at all times. At the same time the initial AUV density is chosen as capable to aggregate a single swarm entity. The control task here considered is thus the implementation of a control input represented by the inter vessel force while being pulled along the x direction, i.e. making the whole swarm follow a linear trajectory.

In the first set of experiments a spherical spatial distribution is reached through the use of a radially symmetrical potential. Subsequently the parameter governing equation (3) is made slowly change and the swarm reacts changing its spatial density. Here are simulated 100 underwater robots, the measures are in meters and the time in seconds.

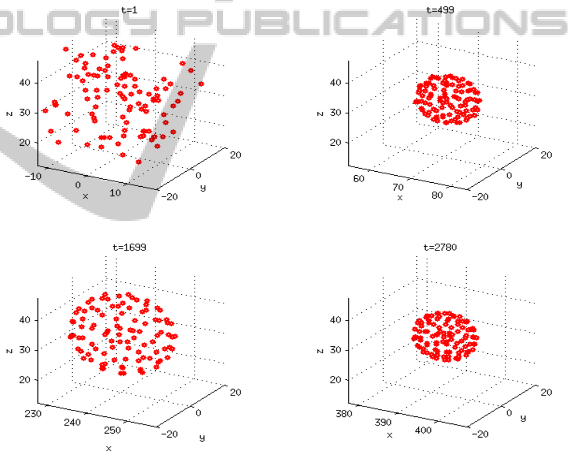

Figure 2: The time evolution of the 100 robot swarm with varying radius.

In figure 2 it can be seen the time evolution of the swarm from an initial random distribution (uniform) inside a box of sides circa 30x30x30 m, to an intermediate stage of spherical distribution of a given average diameter (15m). Then the parameter is further changed obtaining a more diluted formation (circa 25 m) and a final stage with the spherical distribution back to 15m. The average diameter of the spherical formation, $< D >$, and the r_0 of equation (3) are linked by the linear relation: $< D > \cong 1.3\, r_0 - 0.5$.

In the second set of experiments the asymmetrical ellipsoid distance is used to compute the different components of the potential belonging to the different vessels. In figure 3 is shown a swarm of 100 individuals in two final spatial distributions: a flat ellipsoid and a cigar-like one. As an example, the obtained flat formation can be exploited for a search on the sea bed, while the cigar maybe used for communications.

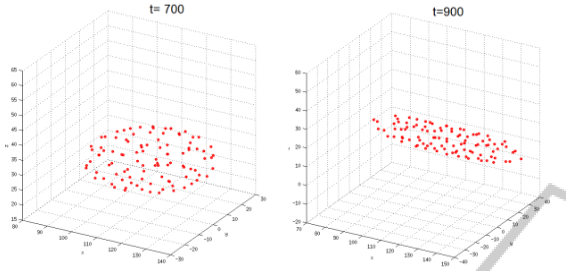

Figure 3: A flat ellipsoidal configuration and a cigar-like one.

5 CONCLUSIONS

This work has been focused on the idea of exploiting the flocking approach not to implement a naturally plausible behaviour, but to make emerge a desired spatial configuration in the swarm. In order to reach this goal some asymmetry has been inserted in the potential functions governing the flocking scheme. To some extent such an idea can be found also in Nature when dealing, for example, with the V-shaped formation of migrating birds.

It has been here shown that through the tuning of a limited set of parameters it is possible to implement different swarm formations that can be useful in different operative contexts. This allows the possibility to contemplate human operator control over a swarm of AUVs and the changing of the swarm formation at the cost of the broadcasting of a few bytes among the individuals.

Further work must be carried out: different three dimensional functions should be studied and simulated in order to find out new spatial configurations. Stability issues must be studied and checked since the here presented simulations have the limit of implying instantaneous communication and awareness among the swarm individuals. This is not the case while coping with underwater vessels whose communication capabilities are limited by the speed of sound. Another issue is the study of the ellipsoidal flock in more complex environments such as the typically considered ones where obstacles or narrow passages can be found, see e.g. (Olfati-Saber, 2006).

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