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Decentralized control of a group of quadcopters using the molecular dynamics method

Децентрализованное управление группой квадрокоптеров использующее идеи метода молекулярной динамики

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Abstract

The development of artificial intelligence systems based on various principles, including anthropomorphic and nature-like systems, as well as progress in the construction of quadcopters for various purposes, made relevant the practical application of these tools for the effective monitoring of underlying surfaces by groups of such devices. The solution of this problem is associated with the effective control of them in conditions of passive and active interference that impedes the fulfillment of missions, as well as with the problem of reconfiguring their construction in case of fail. The model obtained in the work and the calculations made it possible to conclude that the use of the following approach in the future will allow the creation of a self-government system by an independent group of quadcopters, capable of performing various missions without control from the Earth under conditions of active and passive interference, as well as with permanent failure of quadcopters.

Аннотация

Развитие систем искусственного интеллекта, основанных на различных принципах, включающих антропоморфные и природоподобные системы, а также прогресс в построении квадрокоптеров различного назначения, сделало актуальным практическое применение этих средств для эффективного мониторинга подстилающих поверхностей группами таких аппаратов. Решение этой задачи связано с проблемой эффективного управления этими аппаратами в условиях пассивных и активных помех препятствующих выполнению миссий, а также с проблемой реконфигурации их построения при выходе из строя отдельных аппаратов.

Полученный в работе результат и проведенное математическое моделирование позволили сделать вывод о том, что использование подхода основанного на идеях метода молекулярной динамики в перспективе позволит создать систему самоуправления независимой группой квадрокоптеров, способной выполнять различные миссии без управления с Земли в условиях воздействия

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Keywords: computational methods, control, molecular dynamics method, on-board computers, passive and active interference, quadcopter, system.

Introduction

A wide range of various monitoring missions of underlying surfaces makes the problem of controlling a group of quadcopters very relevant. In order to form structures of the moving of these groups, we must solve a number of flight control tasks: providing safe distance between devices, overflights, evasion of aircraft not included in the group, maintaining the system, and rebuilding when losing one or more quadcopters.

Now there are a number of published methods that solve the listed problems separately, but there are no sources about common methods for the whole complex published and available to us, especially in the absence or loss of a leader.

So, the problem of controlling a quadcopter in the group of “leader – slave” is considered using the method that allows controlling the slave one of the group based on information about the movement parameters of it and the relative location of the leader and the slave (Kotov, Maltsev, Nesterov, Sobolev & Yan, 2017). The work does not address issues of compliance with the system and transfer of control in the death of a leader.

For almost the whole set of these tasks, a method for decentralized quadcopter control in a multi-agent system based on modified Reynolds rules (Galustyan, 2017; Reynolds, 1987; Khairnasov, 2020) was developed, which allows changing the leader and flight mode between drill and swarm movements in the course of a collective movement.

In the present work, there is a molecular dynamics method to solve the problem of solution the complete set of flight control problems by a group of quadcopters (Aksenova & Kshevetsky, 2009; Protasov, 1984; Protasov & Bondarenko, 2017; Protasov, Potapova & Sharonov, 2018). Each one is associated with a macroparticle with a given mass, which is affected by the sum of forces from the nearest neighboring macroparticles and obstacles, also

активных и пассивных помех, а также при перманентном выходе из строя отдельных квадрокоптеров.

Ключевые слова: бортовые компьютеры, вычислительные методы, квадрокоптер, метод молекулярной динамики, пассивные и активные помехи, строй, управление.

represented by macroparticles. The force acting on the particulate from the other side is calculated based on the virtual potential of the Leonard-Jones pair interaction (Lennard-Jones, 1924) attributed to each one.

Quadcopter motion control, based on such calculations, does not allow the devices to collide with each other, makes them turn away from obstacles, and move away from the ram (Protasov & Bondarenko, 2017).

A given order is a virtual lattice formed by the centers of mass of quadcopters. After rounding the obstacles, each of the devices tends to take its place there, thereby restoring the system. With the loss of the quadcopter, its place is occupied by the neighboring one. The restoration algorithm of the original structure uses the “annealing” method known in molecular dynamics (Gibson, Goland, Milgram & Vineyard, 1960; Rapaport, 2012). The main idea of this method is the following: when the maximum value of the kinetic energy is reached at a certain point in time, the movement speed is zeroed, thereby achieving the conclusion from the system of excessive and nonequilibrium energy.

In this regard, the main goal of the work is to verify the possibility of using the molecular dynamics method as the basis for constructing a decentralized self-government system for a group of quadcopters that solves the set of above-mentioned problems.

Formulation of the problem

The widespread use of quadcopters is currently limited, firstly, by the vulnerability of remote control systems and, secondly, by the requirement for high-speed communication channels that are difficult to organize, especially for satellite communications. In addition, radio suppression tools can completely paralyze quadcopter control systems of any technical level.

Therefore, there is a need to develop autonomous self-control systems by quadcopters in the complete radio silence mode, for example, using vision systems.

To build a decentralized flight control system for a group of quadcopters, which ensures the fulfillment of the mission, it is necessary to solve a number of problems: ensuring safety when moving a group of devices under external influences, while avoiding obstacles, preventing collisions between quadcopters, and avoiding the ram.

To justify the possibility of constructing this flight control system for a group of quadcopters, approaches based on the ideas of the classical method of molecular dynamics were investigated.

According to the equations of Newtonian mechanics, there are the equations of motion of a macroparticle:

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i, \quad \mathbf{f}_i = m \frac{d\mathbf{v}_i}{dt} = \sum_{j=1, j \neq i}^N \mathbf{F}(\mathbf{r}_{ij}),$$

where t is the time, \mathbf{f}_i is the total force acting on macroparticle number i from the other ones from the system, $\mathbf{F}(\mathbf{r}_{ij})$ is the force acting on macroparticle with number i from the side of macroparticle with number j , N is the number of macroparticles.

The relationship of the force and energy of pair interaction is described by the following equation:

$$\mathbf{F}(\mathbf{r}_{ij}) = -\nabla_i u(r_{ij}),$$

where $u(r_{ij})$ is the potential energy of pair interaction between the macroparticles i and j .

Projections on the coordinate axis of the force \mathbf{f}_i , acting on a macroparticle i , in finite differences can be expressed as follows:

$$F_x = \frac{m}{\Delta t} (V_{x_{t+\Delta t}} - V_{x_t})$$

$$F_y = \frac{m}{\Delta t} (V_{y_{t+\Delta t}} - V_{y_t})$$

$$F_z = \frac{m}{\Delta t} (V_{z_{t+\Delta t}} - V_{z_t})$$

where t is the current time, Δt is the step of integration of the equations of motion in time.

Consequently, the projection of the velocities of the quadcopter in the period of time $t + \Delta t$ is the following:

$$\begin{aligned} V_{x_{t+\Delta t}} &= V_{x_t} + \frac{F_x \Delta t}{m}, \\ V_{y_{t+\Delta t}} &= V_{y_t} + \frac{F_y \Delta t}{m}, \\ V_{z_{t+\Delta t}} &= V_{z_t} + \frac{F_z \Delta t}{m}, \end{aligned} \quad (1)$$

The coordinates of the macroparticles in space in the period of time $t + \Delta t$ can be determined from the following expressions:

$$\begin{aligned} x_{t+\Delta t} &= x_t + V_{x_{t+\Delta t}} \Delta t, \\ y_{t+\Delta t} &= y_t + V_{y_{t+\Delta t}} \Delta t, \\ z_{t+\Delta t} &= z_t + V_{z_{t+\Delta t}} \Delta t. \end{aligned} \quad (2)$$

We selected the Lennard-Jones potential (Lennard-Jones, 1924) to calculate the interactions, which describes Van der Waals interaction of neutral atoms.

A common form of recording this potential is the following:

$$U(r) = 4\varepsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 \right],$$

where σ is the value of the interatomic distance at which $U(\sigma) = 0$, ε is the depth of potential well located at a distance $\sigma \sqrt[6]{2}$, in which the term proportional to r^{-6} , dominates at large distances and corresponds to the dispersion dipole-dipole attraction. The term proportional to r^{-12} , determines the strong repulsion between a pair of atoms due to the exchange interaction, if they are very close to each other. A graph of this potential is shown in the Figure 1.

To speed up calculations, the potential cutoff radius R_{ob} , which allows not taking into account the weak effect of distant macroparticles and the forces acting on them, is artificially introduced. They are calculated only inside the sphere of this radius.

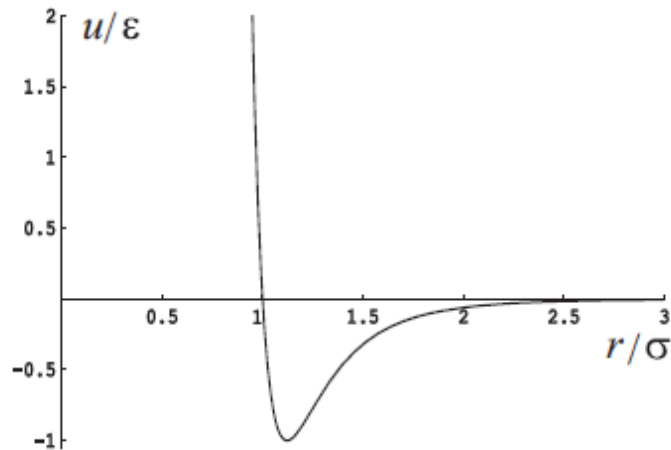


Figure 1. Changing of Lennard-Jones interaction potential

Description of algorithms for calculating the movement of group of quadcopters

When calculating the motion of quadcopters, there are two coordinate systems. The first reference system is a coupled system with the

origin at the center of mass of a group of quadcopters; there, based on the potentials of pair interaction, the velocities and positions of the macroparticles are calculated. This system is shown in the Figure 2.

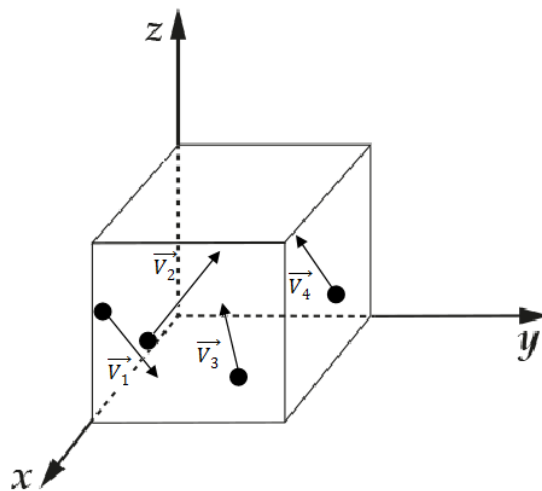


Figure 2. Linked coordinate system

The second coordinate system is connected with the Earth, trajectories of motion of the centers of masses of quadcopters and their speeds are calculated there when performing a given mission. In this case, it is believed that on-board computer of each quadcopter has information about the position of the other ones in the associated coordinate system. This information may come from a quadcopter's vision system.

Initially, the macroparticles simulating the positions of the centers of mass of each quadcopter are located in a face-centered cubic lattice (FCCL) (Protasov & Chudinov, 1982; Protasov, 1984), which has a minimum of potential energy, and in which the resultant forces acting on each macroparticle are equal to zero.

The velocities of the macroparticles in the associated coordinate system are also equal to

zero. When an interaction potential of an extraneous particulate appears in the sphere of action, a disturbance is introduced into the system (Shatalov, Kozlov, Sharonov & Maksimov, 2019).

The macroparticles located in this zone begin to move in a connected coordinate system and exert force on neighboring macroparticles. On-board computers, receiving information about the position of the macroparticles relative to their quadcopter, conduct molecular dynamics calculations of its future position and form a control action.

Description of the process of numerical solution of the problem

The calculations are carried out according to the schemes of numerical integration of the equations of motion (1, 2).

When conducting numerical calculations, the choice of the value of the integration step Δt is very important. As it is known, in excess of Δt of some threshold value, there is a significant loss of calculation accuracy, and after a while, the values of forces, coordinates, and velocities tend to infinity. Usually, researchers using the molecular dynamics method choose Δt in the following way: they set a small value of the time step and gradually increase it until a significant loss of accuracy occurs when repeatedly solving the same problem, then the penultimate value of Δt is used as an integration step.

The use of a selection scheme Δt made it impossible to conduct computer simulation to solve the problem.

Therefore, an adaptive calculation scheme of Δt was proposed in one of the works (Protasov, 1984), allowing to completely exclude the procedure of multiple empirical selection of this quantity.

It made it possible to apply the molecular dynamics method to construct a quadcopter motion control system under various conditions, including ramming with an external object flying at a considerable speed (Protasov & Bondarenko, 2017; Kanashchenkov, Matveev & Novikov, 2018).

There is the following scheme: among all the mutual distances between macroparticles, on-board computers find the minimum distance r_{min} . In the vicinity of this value, the pair interaction potential is approximately replaced

by a parabolic one, in which the second derivative of the potential energy of pair interaction is constant:

$$C = \left. \frac{d^2 U}{dr^2} \right|_{r=r_{min}}.$$

It is known that the period of harmonic oscillations of a macroparticle in such a field is $2\pi\sqrt{\frac{m}{C}}$, where m is the macroparticle mass. In a small neighborhood of the potential acting on the macroparticle, a sufficiently small part of this period can be taken as the value of the integration step. Experience shows that if we select this part in the range from 0.02 to 0.1 of the oscillation period, then there is no divergence in the numerical calculation scheme. In the following work, the value of the integration step is calculated as follows:

$$\Delta t = 0.1\pi \sqrt{\left. m \frac{d^2 U}{dr^2} \right|_{r=r_{min}}}.$$

Based on the above calculation model in the DELPHI environment, there is the written and debugged special simulation program, basic flight modes of quadcopters, correctness of which was controlled by checking the implementation of the law of conservation of energy in the system of macroparticles.

The interaction rules underlying the distributed quadcopter control system are formed based on the molecular dynamics method. In the initial state, in a connected coordinate system, the macroparticles are at rest and the movement of the quadcopter group relative to the earth coordinate system is determined only by the movement, the parameters of which are set in accordance with the specific mission of the quadcopter group.

For any violation of the construction of a group of quadcopters caused by external influence, after its termination, the quadcopter returns to the nodes of the FCCL automatically due to control actions calculated using the "annealing" method (Protasov, 1984; Protasov & Chudinov, 1984; Protasov & Chudinov, 1982; Chudinov & Protasov, 1983; Chudinov & Protasov, 1984; Chudinov, Protasov, Moseev & Goshchitski, 1986; Chudinov, Protasov & Zalukovskaja, 1987). In this case, the kinetic energy of motion in a coupled coordinate system of each quadcopter becomes equal to zero. The cause of the active external influence on the

quadrocopter system can be the appearance of some objects moving in their program that do not belong to the group of quadrocopters and can damage one of the devices.

In this case, an artificial macroparticle with also a pair interaction potential is introduced into the calculation algorithms, and a disturbance is introduced into the group motion. Quadrocopters leave their equilibrium positions, and each one in this coordinate system has kinetic energy that can lead to chaotic motion of quadrocopters and loss of order. Then, in accordance with the method of "annealing", the velocities are zeroed in the bound coordinate system. Zeroing cycles are carried out until all excess energy has been removed from the system. Usually, about ten of these artificial influences are sufficient, and after

they are stopped, the quadrocopters occupy an equilibrium position again.

In the same way, the effects of motionless in external interference (walls), which are simulated by a grid of motionless macroparticles in the earth's coordinate system, are taken into account. "Annealing" of such a system occurs in a similar way.

Depending on the properties of the external obstacle, a group of quadrocopters will either fly around such an obstacle or "leak" into the obstacle window, automatically restoring the system after the end of the interference. The quadrocopter control circuit is shown in the Figure 3.

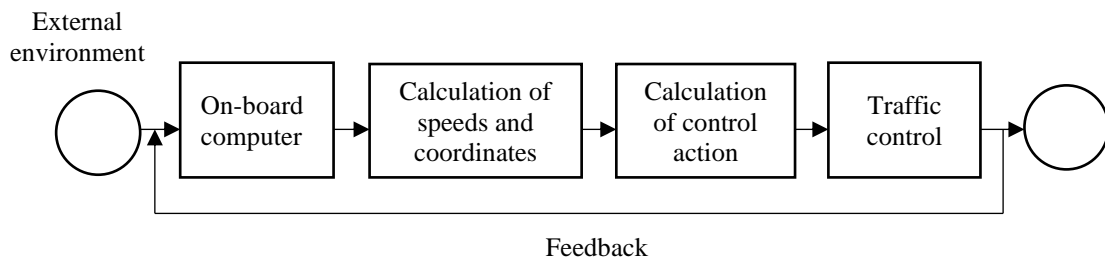


Figure 3. Quadrocopter control circuit

Experiment results

The possibility of using the molecular dynamics method for macroparticle systems simulating a group of quadrocopters was tested in the DELPHI software environment by computer simulation for groups of 40 macroparticles (quadrocopters), it is not a member of the group, but approaches to it.

The system of macroparticles was formed as follows: in the Earth's coordinate system, the initial state was set in the form of random macroparticles located in space that imitate quadrocopters. Distances between the nearest macroparticles ranged from 0.7 to 1.3 equilibrium distances. Four quadrocopters were located in the center of the system, the centers of mass of which were located at the vertices of the tetrahedron, with an edge length equal to the equilibrium value for the FCCL structure when the Lenard-Jones potential was used in the

calculations. The use of the annealing method led to the gradual ordering of macroparticles into the FCCL structure.

When establishing the kinetic energy of the system close to zero, a macroparticle was sent to the center of the group, which is not a member of it. The mission of this macroparticle was to make a collision with one of the central ones.

The simulation results and analysis of the motion of individual macroparticles (quadrocopters) showed that no collision occurred, the group scattered, giving a corridor to the incident macroparticle, and after removing it to a distance exceeding the radius of action of the pair interaction potential, the system was restored.

Figure 4 shows the time dependence of the kinetic energy of some macroparticles (quadrocopters) with a group size of 40 macroparticles (quadrocopters).

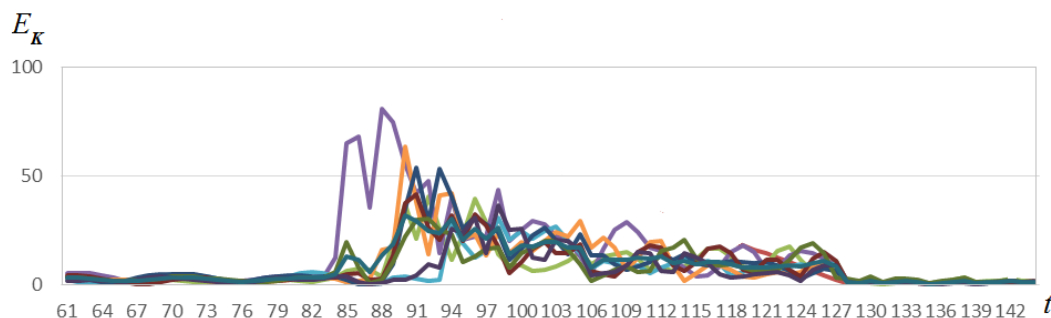


Figure 4. Kinetic energy dependence E_K of quadrocopters from time t

An analysis of the time dependences of the kinetic energy of the quadrocopter group in the Figure 4 showed that at steps 61-82 the group was at rest. Then, in step 83, quadrocopter, flying a ram, flew up to the group. It can be seen from the figure that at steps 83-94, disturbance was introduced into the system and quadrocopters began to move in a connected coordinate system, moving away from the collision. Then, at step 88, a process resembling a cascade of atom-atom collisions in a solid began (Protasov & Chudinov, 1982; Chudinov & Protasov, 1983; Medvedev, Vasilyev & Sokolsky, 2019).

After the collision threat disappeared, at temporary steps 129-143 in the group, as a result of the inclusion of the “annealing” mode, restoration of the system began. Upon completion of this regime, the macroparticles again regained their equilibrium positions in the nodes of the FCCL.

The mathematical modeling of the tasks is the following: restoration of the system after the removal of several macroparticles (dropping of quadrocopters to the Earth), group of macroparticles (quadrocopters) bending around a stationary obstacle, group passing holes in an obstacle with dimensions smaller than the “diameter” of the group structure.

In all cases, the restoration of the formation of macroparticles (quadrocopters) into the FCCL after the cessation of external interference to the group was also observed.

Conclusion

The paper presents the results of computer simulation of a decentralized flight control system of a group of quadrocopters, confirming the hypothesis about the possible use of molecular dynamics methods to create decentralized group control systems that exclude

collisions of quadrocopters with each other and with obstacles, ram evasion, and recovery after termination of external interference.

Modeling was carried out using the software package developed for these purposes in the DELPHI environment.

It is concluded that the use of the proposed approach in the future will create a control system for an independent group of quadrocopters, capable of performing various missions without control from the Earth under conditions of active and passive interference, as well as with the permanent failure of individual quadrocopters.

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