Estimation of Energy Costs in a Network Cyber-Kinematic System with Mobile Devices

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Abstract — The object of research in this article is a ubiquitous sensor communication network, consisting of sensor nodes that control the physical space, moving in space according to a certain law of motion, and a base station that accumulates information, processes and makes prompt decisions. The subject of the research is the energy consumption models of the ubiquitous sensor network, which provides interaction between sensor nodes in the physical and information space. The purpose of the study is to identify the mutual influence on energy consumption during information interaction of sensor nodes, taking into account the law of motion in space. The paper gives definitions of a certain class of cyber-physical systems. An estimate of energy consumption for organizing data transmission between a mobile sensor device moving in space according to a given Dubins law of motion and a base station is proposed. Also presented is the solution of a two-point control problem for the kinematic component of a network cyber-physical system using a discrete-switchable control function.

Keywords— cyber-physical system, discrete-switchable control function, Dubins law, energy consumption, movable sensor node, ubiquitous sensor network

I. INTRODUCTION

The cyber-physical system is a complex system of a new generation, which includes two key, and possibly more, components: cybernetic and physical. The physical component provides real-time data collection from the physical world and information feedback from cyberspace, the cybernetic component provides intelligent data management, analytics and computing capabilities that are created in cyberspace.

In 2009, in [1] W. Wolf suggested that cyber-physical systems may well become the theory that will contribute to the development of high-performance computing. This means that such systems must provide a new level of performance and efficiency thanks to the complex code scheme of control computations. Cyber-physical systems actively interact with the real world in real time and consume real energy. Research [2] gives the following definition of a cyber physical system (CPS) - these are physical and engineered systems, the operations of which are monitored, coordinated, controlled and integrated by the computing and communication core. Just as the Internet has changed the way people interact with each other, cyber-physical systems will change the way we interact with the physical world around us. Complex ones arise in such areas as transport, healthcare, manufacturing, agriculture, energy, defense, etc. The design, construction and testing of cyber-physical systems pose many technical problems that must be solved in the near future.

The article [3] is devoted to the design of cyberphysical systems using more advanced models: the PRET model, which allows you to show how accurately the process of synchronizing digital logic is performed at the software abstraction level; the Ptides model (programming of time-integrated distributed embedded systems), which shows that deterministic models for distributed cyber-physical systems have practical exact implementation.

In the work [4], the Markov model of reliability of a fault-tolerant cluster performing calculations in a cyber-physical system is considered. The results of the article are aimed at the possibility of assessing the likelihood of a cluster's operability, ensuring the continuity of computations and its operation until failure, leading to the interruption of the computational process (control) beyond the maximum allowable time. The presented solutions are aimed at homogeneous cyber-physical systems, i.e. on systems that can be described using deterministic models, both cybernetic components and physical. However, in real life, this approach is imprecise, because the physical process in most cases is a nondeterministic, nonlinear process.

II. METHODS

To build a model, it is necessary to solve several interrelated problems. The proposed model consists of three parts. The first part of the model allows to solve a twopoint problem of motion control of a kinematic nonlinear system, which characterizes the movement of the sensor unit according to a certain law of motion. For this, the Hilbert Uniqueness Method is used, which consists in reducing the problem of local controllability of a nonlinear control system to the existence of corresponding periodic trajectories and studying the controllability of already linear systems [5, 6]. The second part of the model allows solving the problem of controlling the cybernetic component, applying a multi-agent approach to the network communication layer, introducing the concept of speed control based on interaction into the structure of explicit speed control of communication networks, presented in the book [7]. In this case, each router (server or switch) interacts with its neighbors and adjusts the queue length based on one-stage information about the queue of neighbors' bottlenecks in accordance with a specific cooperative algorithm that operates at the network layer of a multi-level control system. The third part of the model is designed to estimate the energy consumption for the transmission of information from the mobile sensor node to the base station. For this, the approach developed in [8].

III. DEFINITION OF A CERTAIN CLASS OF CYBER-PHYSICAL SYSTEMS

In this paper, the definitions of cyber-physical systems are clarified from the point of view of the implementation of a physical process.

A cyber-mechanical system is a networked system of mobile devices that change over time their location on a plane or in space, interacting with each other and the external environment, integrating computing, communication and control technologies.

A cyber-electrodynamic system is a networked system of devices interacting with each other and the external environment through electromagnetic fields, which integrates computing, communication and control technologies.

A cyber-optic system is a hybrid system that includes elements of the physical world that interact with each other and the external environment through the use or detection of the behavior and properties of light, and integrates computing, communication and control technologies.

A cyber-kinematic system is a network system of mobile devices that change over time their location on a plane or in space, interacting with each other and the external environment, having a mutual effect on each other, integrating computing, communication and control technologies.

The presented definitions represent a new hybrid approach to solving complexly structured problems, in which it is necessary to take into account the dynamics (development) not only physical (spatial and temporal), but also informational.

For sensor networks with moving nodes, cyberkinematic models are needed, which should describe the motion of these conditions, in the simplest case by rectilinear equations, but in the most general plan by a nonlinear system of differential equations. In the second case, in particular, the movement of sensory nodes can be described by the Dubins model.

IV. NETWORKED CYBER-PHYSICAL SYSTEMS

Networked cyber-physical systems are fundamentally different from standard distributed systems in that the dynamics of the network affects the performance and physical dynamics of the closed-loop system. This interaction of three components: physical, cybernetic and network, and such an architecture significantly reduces the complexity of solving difficult formalized and poorly structured control problems.

Of course, wireless networks offer lower costs, better power management, easier maintenance, and easier deployment in remote and hard-to-reach locations. Thus, cyber-physical systems in conjunction with a wireless sensor network make it possible to implement large-scale projects and bring decision-making to a new, higher quality level. In an industrial environment, vital information can be transmitted over communication channels between mechanisms, control and monitoring devices, which must be transmitted in short ”packets”, which requires a relative bandwidth and connection speed. On the other hand, transferring large files such as production logs or real-time media transfer requires very efficient transfer of large amounts of data [7]. Therefore, one of the most important requirements is reliability and timely delivery without interruptions [9].

Therefore, one of the most important requirements is reliability and timely delivery without interruptions. Choosing the right wireless networking solution in an industrial environment requires high communication performance without sacrificing speed, flexibility, range, or reliability. A wireless CFS is characterized by physical network limitations, packet loss and latency, which in turn affect the performance of the entire surveillance / control system. The aforementioned disadvantages are especially relevant in the case of wireless communication, where the presence of collision and common channel phenomena can significantly degrade performance and even affect the stability of the closed loop [10, 11, 12, 13]. Various models and theoretical approaches were presented to analyze and study the stability of the CPS network [14, 15], stochastic protocols [16], real-time planning [17].

A. The control problem of networked cyber-kinematic systems

Consider the following architecture of the cyberkinematic system (Fig. 1). A networked cyber-kinematic system consists of a ubiquitous network of nodes used to monitor or control a given distributed physical system and a fixed base station.

Suppose each sensory node can be represented as

- a sensor for measuring the local physical variable of interest,
- a controller for implementing a control command,
- transit or hop for forwarding or generating packets,
- a node that has the ability to move in space (robot, quadcopter, car, tractor, etc.), and performs the assigned tasks (collection, transfer, aggregation and/or storage, etc.).

Each presented sensor node can interact with another sensor node, which in turn increases the complexity of the control task and the problem of formalizing the cooperation infrastructure, which in turn affects packet loss, time delays, power consumption, etc., and, consequently, on the performance of the entire cyberkinetic system as a whole.

Consider a control system of the following type [7]

$$x = f(x, u_x, q, \tau_{kn}) \quad (1)$$

$$q = g(q, u_q, \tau_{kb}) \quad (2)$$

where x is a measure or estimate of a variable of a distributed physical process (possibly a random variable) that needs to be monitored or controlled; q is the queue length on the router / switch (wired / wireless / ubiquitous) communication network; τ_{kb} is the network cyber time delay associated with the delay caused by the communication network protocol / architecture (eg propagation delay, collision phenomena and queue delay); τ_{kn} is the kinetic level time delay affecting information x due to τ_{kb}, sampling delay, computation delay, and compression measurement delay; $u_x = u(x)$ and $u_q = u(q)$ are, respectively, control applied at the application and network layers.

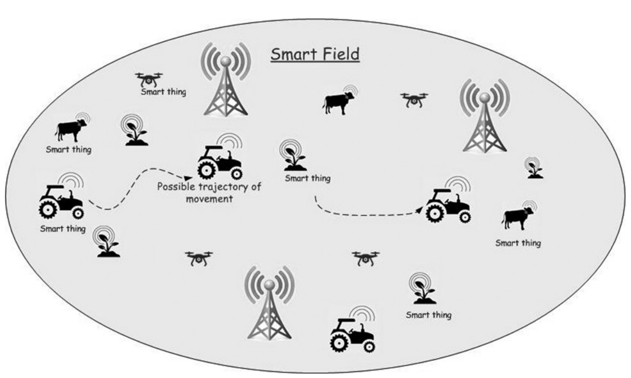

Fig.1. Sensory field

First equation (1) represents the model at the application layer, and the second (2) represents the dynamics of queues at the network layer. In [7] considered the development of hybrid control laws u_x and u_q, leading, respectively, to an application-level control system and a network-level control system. The setpoints q_0 and x_0 are fixed according to the characteristics required by the network and the application management system, respectively. A significant drawback of this work is the study of the issue of controllability only for linear and representative models.

In this paper, the issue of interaction of the nodes of the sensor network and the organization of data transfer between them is upset, provided that these nodes move in space according to a certain nonlinear law of motion control, which is most close to reality.

Suppose the nodes move according to Dubins' law and the directions of movement are bounded. According to the presented law, there is a mechanism that has the ability to regulate the movement of a physical component according to specified parameters. There is also a cybernetic mechanism that allows you to determine the state and position of a mobile sensor device in space, for example, by determining GPS coordinates.

B. Node movement models

Wireless sensor networks with mobile nodes are more efficient than stationary ones. There are various models of node movement in a wireless sensor network.

The Dubins model is used to control wheeled robots [18], for dispatching calculations in civil aviation [19], as well as in applied work on constructing trajectories of unmanned aerial vehicles in a horizontal plane [20].

The Random Walk Mobility Model assumes that the node moves in its chosen direction at a certain speed, which is given by a uniform (or Gaussian) distribution law for a period of time given at the beginning of the simulation. After the node reaches the border of the area covered by the WSN, the node changes direction depending on the angle of reflection from the border [20].

In Random Waypoint Mobility Models, a node starts moving in the direction of a given point at a speed that obeys a uniform distribution law. Upon arrival at the destination, a new point is determined in the direction to which the node continues to move [20].

The Gauss-Markov model allows you to adapt to random processes by adjusting certain parameters. The modeled node is given speed and direction, after a certain period of time the direction and speed change to new ones that obey the Gaussian law of distribution of random variables.

The Manhattan motion model is proposed to a greater extent for tracking the movement of nodes in an urban area. Nodes move only in a horizontal or vertical direction, along marked sections of streets, this model is similar to the model of movement along the highway, the only difference between the Manhattan model is that when crossing streets, the node with a certain probability chooses to turn right or left [20].

V. ESTIMATION OF ENERGY CONSUMPTIONFOR INFORMATION TRANSMISSION

Let $l = l(\tau, x_0, x_\tau)$ denote the path of motion of the sensor node from point x_0 to point x_τ for some time τ. Suppose that there is an optimal trajectory for solving the two-point problem *l*. It is necessary to quickly track the coordinate location of the sensor node and compare the real trajectory of movement with the given one. If the sensor node deviates from the optimal trajectory, it is necessary to adjust the control action to return to the specified trajectory. These actions are subject to restrictions related to the complexity of computational processes and an increase in the speed of execution.

As a model of optimal motion, consider a system of n nonlinear ordinary differential equations of the form:

$$\frac{\partial x_i(t)}{\partial t} = f_i(t, x_1, \dots, x_n), i = \overline{1, n}. \qquad (3)$$

The motion of a system with a given initial condition, in which deviations from the given initial values have occurred, are called disturbed motion.

If we talk about the return of the sensor node to the optimal trajectory, then at each moment of time it is necessary to solve the two-point problem and the stability problem, and, based on the decision, make a decision about moving the node to a given point. Unfortunately, in real life, nonlinear conservative dynamical systems are usually not asymptotically stable. Asymptotic stability generally corresponds to asymptotically stable motion with respect to any initial deviations. Any arbitrarily small change in the initial conditions leads to a change in the motion parameters, which means that even greater restrictions are imposed on the information component of the cyber-kinematic system and computational loads increase.

This section presents a possible estimate of the energy consumption for transmitting a data block from a mobile sensor device to a fixed base station.

Suppose that there is a stable solution to system and denote it as $\tilde{x}(t, \phi(t))^2$. Then the distance traveled by the sensor node from the given starting point x0 to the point x_τ will be found as follows:

$$\bar{r} = \sqrt{\tilde{x}(t, \phi(t))^2 - x_0^2} \qquad (4)$$

Substituting (4) into the Friis formula [22, 23, 24, 25], we can find the energy consumed for transmitting information to the base station at the time τ:

$$\bar{P}_{tr} = \frac{16 P_r \pi^2 r^2 f^2}{G_{tr} G_r c^2} \qquad (5)$$

where G_{tr} is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, P_{tr} is the radio signal power at the transmitting antenna [W], P_r is the power of the radio signal at the received antenna [W], r is the distance between the antennas of the mobile sensor devices of the ubiquitous sensor network in meters, c is the speed of light, f is signal flow frequency.

It follows from the Friis formula that reducing the distance between two mobile sensor devices by 2 times reduces the energy consumption for transmitting a data block from one to another by 4 times.

The average energy spent on the transmission of one data block to the base station from a sensor device located at a distance r from the base station is denoted as:

$$\bar{e}_c = \bar{P}_{tr} \cdot \tau \qquad (6)$$

To obtain the average energy spent on the transmission of information of all sensor devices, it is necessary to sum all possible energy consumption at the average values of the distances from the sensor device to the base station.

VI. CONCLUSION

The paper gives definitions of a certain class of cyber-physical systems. An estimate of energy consumption for organizing data transmission between a mobile sensor device moving in space according to a given Dubins law of motion and a base station is proposed. Also presented is the solution of a two-point control problem for the kinematic component of a network cyber-kinematic system using a discrete-switchable control function. With such a law of motion of these sensor devices in the sensory space, the proposed model will significantly reduce the energy consumption required for the interaction of mobile sensor devices. In the future, it is planned to present solutions to the control problem at the cybernetic / network level and propose models of the total energy consumption for the implementation of hybrid control, which makes it possible to take into account all possible limitations and disadvantages at each level.

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