Air Cushion Vehicle Model for Educational Purposes

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ABSTRACT
The paper introduces the model of the air cushion vehicle which is used to teach students control theory methods at the Saint-Petersburg State University. The model can operate either in the remote control mode or in the autopilot mode. Various tasks can be solved using this model: from the course stabilization to the dynamic positioning. Linear model and some experimental results are presented.

Categories and Subject Descriptors
I.2.9 **[Artificial Intelligence]**: Robotics – *autonomous vehicles*.

General Terms
Design, Experimentation.

Keywords
Control theory, education, marine systems, regulator, remote control, robotics.

1. INTRODUCTION
Nowadays we can observe the complication of the various vehicles. One of the brightest examples in the area of marine crafts is the class of air cushion vehicles (ACVs). The main feature of such crafts is the reduction of the water drag by creating the area of pressurized air between the water and the hull. For the crafts with the flexible skirt surrounding the air cushion this feature allows to operate not only in the water, but on the different surfaces: ground, ice, swamp, etc.

Due to the increasing requirements and restraints for the dynamics of all kinds of vehicles in different modes of operation there's a need in control theory specialists. Such specialists must know the whole process of the analysis of the plant dynamics and the synthesis of control law from the mathematical and computer model to the implementation of the control system. Thus, it's important to teach students not only the control theory methods, but also to provide a significant practice with various real-world vehicles.

For this purpose here at the Saint-Petersburg State University we've built the model of the ACV. It has 32-bit controller and several sensors, including inertial measuring unit and onboard webcam. The model can operate in two modes. The first one is the autopilot mode when there's a program executing on the controller. The second one is the remote control mode, either manually via the mobile application or automatically via remote computer.

The model can be used in various tasks, such as model identification, course stabilization and control optimization. Some complications can be added to the basic tasks, such as use of the dynamic observers, filters or introducing delays into the control system (in the remote mode). All these tasks require knowledge of applied mathematics and programming skills, giving a good representation of the process of designing real control system.

2. THE MODEL
2.1 Structure and actuators

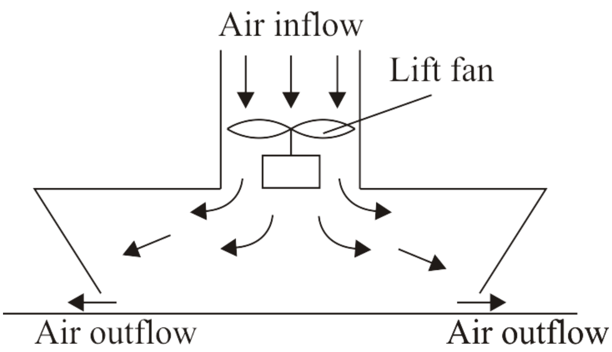

Figure 1. Plenum chamber air cushion.

The model represents a simple plenum chamber hovercraft where air directly fills the air cushion (see fig. 1). Although it is not the most efficient scheme for creating the air cushion it is the easiest one. There's one lifting fan and one thrusting fan (both with 1400 revolutions per minute per volt motors and individual voltage regulators). Thrusting fan is equipped with relay to change the direction of the motor. There are three synchronized air rudders with one servomotor to control the turn of the craft. The hull is made of extruded polystyrene (xps) and the skirt is made of artificial leather. Fan duct, rudders, lifting fan safety net and ultrasonic sensors' hulls are printed on the 3D printer. There are three 11.1V Li-Po accumulators: one for each fan's motor and one for the controller. The ACV model is presented on the fig. 2.

Figure 2. ACV model.

There's no cushion compartmentation (the air cushion is not divided into sections) so there're no restoring moments for the roll and pitch angles. Therefore the craft is quite sensible to the arrangement of all onboard components (especially accumulators). Non-zero roll angle produces lateral jet flow from the air cushion which affects the stability of the craft. All components must be placed quite carefully and fixed well to achieve satisfactory balance.

2.2 Controller

We're using TRIK controller [2] which is designed for using in various cyber-physical systems. It's based on the 375 MHz ARM9 processor and has 256 Mb of RAM memory. It also has additional discrete signal processor (DSP) which can, for example, process images from the camera without loading the main processor. The controller has onboard Bluetooth and Wi-Fi chip which can work either as network access point or as a client, so it is possible to communicate with TRIK remotely, for sending control commands or for streaming the camera video. There's also the peripheral processor which is capable of controlling all of the 19 general purpose digital ports and 4 motor ports. This processor allows to directly plug motors and servomotors to the controller without using additional drivers. There are also onboard gyroscope and accelerometer and one USB port.

There are several ways to program the controller depending on the students' programming skills. The easiest way is to use the open-source TRIK Studio IDE. There's a special visual language in which the program is structured as a sequence of visual blocks (see fig. 3). After creation the program can either be uploaded on TRIK via Wi-Fi or executed in the interpretation mode without uploading. It's also possible to use C++, C#, F#, Python, Java, JavaScript or QtScript languages. Such wide range of the available languages allows using this controller with minimal training time.

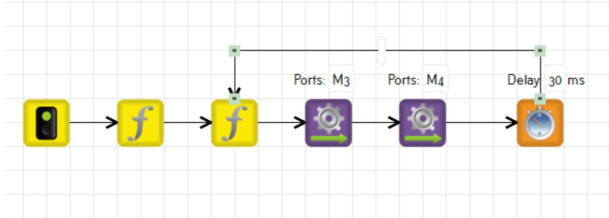

Figure 3. TRIK Studio program.

Another way is to build the remote system where the craft is used as an agent executing the control commands received from the remote computer and sending back its state's measurements. Here we can formulate two types of tasks: manual and autonomous remote control. In the first case students learn the basics of network communication. There's a convenient programming interface for this task made by TRIK team which allows creating such systems quite rapidly using the TCP sockets communication. In the second case the whole control system can be considered as a time-delay system and the corresponding problems can be formulated and solved.

2.3 Sensors

Although the controller has its own gyroscope and accelerometer it's very hard to get the stable measurements of the course angle without integration errors. So there's a need to use additional sensor such as magnetometer. We decided to use MPU-9250 inertial measurement unit which has 3-axis magnetometer, accelerometer and gyroscope. The main advantage of this chip is presence of the integrated digital motion processor (DMP) which receives data from chip's sensors and uses its own filters and algorithms for calibration and calculation of the stable and low-noise orientation angles. Of course it's also possible to get the raw data from each unit's sensor, so we can set and solve the filtering tasks also. MPU-9250 communicates with TRIK via the I2C interface.

There are three range sensors mounted on the front side of the ACV: two ultrasonic and one infrared. They allow solving tasks such as moving along the corridor and obstacle avoidance. In these tasks students can learn the basics of the proportional–integral–derivative (PID) regulators.

There's also the webcam which allows solving various computer vision tasks and to extend the use of the PID-regulators or to try more complicated methods (for example, visual servoing [1]).

3. PROJECTS AND FEEDBACK

During the last year we've been offering 3 projects to the students. The first project was to build the manual remote control system for the craft. The project was divided into 3 parts: developing the program in the TRIK Studio for receiving and performing the control commands on the onboard controller; developing the program for the desktop computer in the C++/Qt for sending control commands; developing the program for the onboard controller with the C++/Qt and replace the TRIK Studio program. Students that worked on this project said that it was quite interesting to build a system that actually allows you to control the real moving object and to feel what it's like to be the remote operator. And of course it was a great demonstration of the basics of the practical side of the network communication and cross-compilation, because programs for the TRIK controller must be compiled on the desktop computer.

The two other projects are devoted to the control theory. The first of them was moving along the corridor. As mentioned in the previous section, there are three range sensors in front of the craft. The task was to move forward autonomously in the center of the corridor with some smooth turns and to stop or move backwards if there's and obstacle closer than 1 meter. This task introduces the students to the work with sensors and to the concept of the PID regulators. Most of the students working on this project said that at the first sight the task seemed much harder than it actually was and that after solving it they have a deeper understanding of what the concepts of feedback and regulator mean in control theory. Of course, the process of selection of the PID coefficients was not so easy and required a lot of experiments, but the concept itself was understood quite well and easily.

The last project was very close to the real problem for the different kinds of crafts. The task was to build an autopilot which must turn and keep the course angle on the desired level. In this project we're teaching the students the basics of the control law described in the next section. It requires knowledge of the linear model and could meet various requirements for the control quality. As we could conclude from the students' feedback, the main advantage of this task was not only the deeper understanding of the control law, but the connection between abstract mathematical models and real-world tasks, the idea that complex mathematical methods can be very useful in practical problems.

4. MULTIPURPOSE CONTROL LAW

Here we show the example of the educational task of the course stabilization in the simplest case. Let us consider the linear model of the craft. As stated in [4], linear models of the lateral motion of the real ACVs consist of drift, course and roll angles and of the angular velocity. But for our model it was enough to consider only angular velocity and course angle.

If we assume that the craft's moving with some constant longitudal velocity, zero angular and lateral velocities, zero rudders angle and without external disturbances, then the linear model of the course angle's dynamics can be expressed as follows:

$$\begin{aligned} \dot{\omega}_y &= a\omega_y + b\delta, \\ \dot{\varphi} &= \omega_y, \end{aligned} \tag{1}$$

where ω_y is the angular velocity, δ is the rudders angle and φ is the course angle. For our craft moving at the speed of 1.5 m/s coefficients in the right part of the linear system (1) have the following numerical values:

$$a = -0.147, b = 0.582.$$

In addition to system (1) we consider linear model of the rudders actuators:

$$\dot{\delta} = u, \tag{2}$$

where u is the control signal.

The system (1) – (2) is the linear time-invariant (LTI) system. If we assume that we can measure only the course angle, then the system (1) – (2) can be rewritten in the general matrix form:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \mathbf{B}\delta, \\ \dot{\delta} &= u, \\ y &= \boldsymbol{C}\boldsymbol{x}, \end{aligned} \tag{3}$$

where y denotes the measurements and

$$\boldsymbol{x} = \begin{pmatrix} \omega_y \\ \varphi \end{pmatrix}, \mathbf{A} = \begin{pmatrix} a & 0 \\ 1 & 0 \end{pmatrix},$$
$$\mathbf{B} = b, \mathbf{C} = \begin{pmatrix} 0 & 1 \end{pmatrix}.$$

There exist various methods of stabilization of LTI-systems: pole assignment, linear quadratic regulators (LQR), PID regulators, etc. In our educational process we focus on the so-called multipurpose control laws [3] which take into account constant and periodical external disturbances such as wind or waves. In case of the wind the controller minimizes the course deflection and then makes the course angle converge back to the desired level. In case of the waves the controller can either provide accurate steering or minimize rudders deflections. One of the main advantages of such control laws is that the main task is divided into the smaller subtasks which are solved independently. It is also possible to switch off some parts of the controller for some computational economy, for example, on the calm water.

Multipurpose controller has the following structure:

$$\begin{aligned} \dot{\boldsymbol{z}} &= \mathbf{A}\boldsymbol{z} + \mathbf{B}\boldsymbol{\delta} + \mathbf{G}(\boldsymbol{y} - \mathbf{C}\boldsymbol{z}), \\ \xi &= F(p)(\boldsymbol{y} - \mathbf{C}\boldsymbol{z}), \; p = d/dt, \\ u &= \boldsymbol{\mu}\dot{\boldsymbol{z}} + \boldsymbol{\upsilon}\boldsymbol{y} + \xi. \end{aligned} \tag{4}$$

The first equation of the system (4) is the asymptotic observer which is used for estimation of the whole state of the system based on the measurements. Matrices **A**, **B** and **C** are from system (3). Vector $\boldsymbol{z}$ is the estimation of the state vector $\boldsymbol{x}$ and y denotes the measurements. Matrix **G** is selected so that the estimation converges to the state of the system.

The second equation of the (4) represents the dynamic corrector (or filter) which is responsible for dealing with periodical disturbances. Transfer matrix $F(p)$ is selected so that the effect of the disturbances is minimized and the control requirements are met.

Finally, the last equation of the (4) is the speed control law which provides stabilization of the system (3) with astatic property (i.e. stabilization to desired level even in the presence of constant disturbances) and minimizing the periodical disturbances. Coefficients $\boldsymbol{\mu}$ and $\boldsymbol{\upsilon}$ are selected in order to stabilize the system (3) with desired control requirements.

In our case asymptotic observer has the following form:

$$\begin{aligned} \dot{z}_1 &= az_1 + b\delta + g_1(\varphi - z_2), \\ \dot{z}_2 &= z_1 + g_2(\varphi - z_2), \end{aligned}$$

where $g_1 = 0.8412$ and $g_2 = 1.6378$.

Accordingly, the speed control law looks like this:

$$u = \mu_1 \dot{z}_1 + \mu_2 \dot{z}_2 + \upsilon\varphi,$$

where $\mu_1 = -3.1525$, $\mu_2 = -3.0483$ and $\upsilon = -1.8784$.

Fig. 4 demonstrates the craft's turn on 10 degrees without external disturbances.

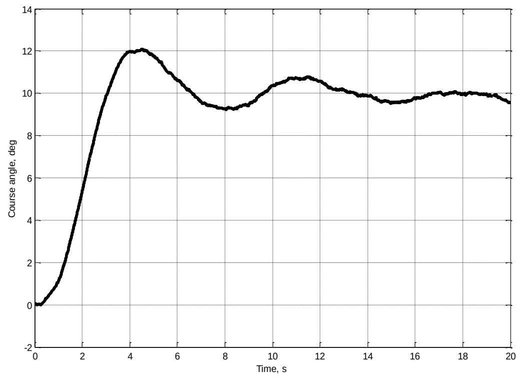

Figure 4. Course angle stabilization.

5. CONCLUSIONS

In this paper we presented the ACV model which we are using to teach student programming, applied mathematics and control theory methods. One year experience showed that it is much more interesting for students to work with real-world object and solve real tasks than to consider only computer models.

Of course there are still a lot of things that we wish to do. First of all, it is important to try cushion compartmentation to get the restoring moment and achieve zero roll and pitch angles. Another thing is to implement different technique of the air cushion formation: for example, momentum curtain, which should be more effective than simple plenum chamber cushion. It is also interesting to add second thrusting fan to make it possible to control the turn by the difference of thrusts.

So far we've been driving the craft only above the flat surfaces. Of course, it is very interesting to try motion above the water surface to get comparison to the dynamics above the usual flat surface as floor and to test the multipurpose control law in the case of water waves.

6. REFERENCES

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