Design of an autonomous remote control hovercraft with image recognition technology

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This study mainly focuses on the design of an autonomous remote control (RC) hovercraft. In the control design of hovercraft, we apply a fuzzy gain scheduled integral scheme to deal with the uncertainties of nonlinear system. In the implement system, the BASIC Stamp micro-controller is applied as control center to perform tasks. In addition, the ultrasonic sensor is used for providing the function of obstacle avoidance, and the camera installed on hovercraft is able to catch the immediate image. With the application of image recognition technology, the developed RC hovercraft possesses the capability of recognition and navigation. The experimental results indicate that based on the proposed method the RC hovercraft can be autonomously navigated to the target.

Keywords: RC hovercraft, Autonomous control, Fuzzy gain scheduled, BASIC Stamp, Obstacle avoidance, Image recognition technology

In addition to conveyance, the hovercraft is capable of amphibious operation and obstacle surmounting. Compared with traditional boats, the hovercrafts provide faster speed and better reaction capacity. By the innovation of shipbuilding engineers and scientists, hovercrafts have been ameliorated for running on water, land, beach, ice, and marsh in high speed. The hovercraft owns the properties of all kinds of vehicles even though it does not belong to the truck, boat, and aircraft. The hovercraft overcomes the constraints of less traffic, slow speed and limit distance which are respectively possessed by aircrafts, ships, and trains. Therefore, the product of hovercraft is valuable in commerce. Many manufactories have focused on the relating development of hardware, material, and industrial technology. However, the hovercraft is a highly nonlinear system which is not easily handled in a stable motion. Various environmental conditions, such as meteorology and topography, should be considered in the control. Therefore, how to accurately and steady control the hovercraft is still an important investigation issue.

Most of popular hovercrafts are operated by manual or semi-automatic methods. Few operations of hovercraft are based on automatic navigation method. Referring to the previous methods proposed in literature, we understand that intelligent methods have been applied for various kinds of vehicles. Soliman developed a Fuzzy-based control for active suspension systems applied to a full vehicle model. Kwak and Park proposed their recent study results on the mobility of service robots in 2012. Accordingly, it is reasonable to develop an autonomous hovercraft which will be potential for the application of surveillance on the sea. In the previous investigation results, we also have successfully developed a fuzzy gain scheduled integral control law for the hovercraft. Furthermore, the proposed scheme has been realized by CPLD. The experimental results indicate that the hovercraft could be resulted in a good tracking control based on a fuzzy gain scheduled method. In this paper, we extend the previous investigation results to design an autonomous RC hovercraft. The main feature of the developed system is to apply the recognition technology for achieving the function of navigation. With the integration of center controller and various sensors, the hovercraft is able to avoid obstacle. Consequently, the navigation strategy and the image recognition technology are incorporated in the RC hovercraft to help achieve localization.

Many control schemes of hovercraft have been proposed in literature. In 1999, Fantoni et al. proposed three kinds of control law for the hovercraft to satisfy the following conditions, respectively.
(i) globally asymptotically stability, and inputs converge to zero, (ii) global exponential stability, one boundary input and one input converge to zero, and (iii) global exponential stability, and inputs converge to zero. In addition, Tanaka et al.\textsuperscript{12}, Tunstel et al.\textsuperscript{13}, Barbero-Kinan and Sigalotti\textsuperscript{14}, Sira-Ramirez\textsuperscript{15} and Defoort et al.\textsuperscript{16}, proposed applying switching fuzzy control, fuzzy method, configuration tracking control, sliding mode control and high order sliding mode control scheme, respectively, for the tracking control of hovercrafts. By the above developed methods, the hovercrafts seem to be controlled within a small region. However, the tracking responses indicate that there is still a potential for improvement.

On the other hand, the machine vision has been successfully applied for the position control of robots, servo systems, and various regions\textsuperscript{17-19}. Some scholars also utilized the machine vision for controlling the dynamical behaviors of ground type robots\textsuperscript{20,21}. Moreover, the application of machine vision for the autonomous flying robot is famously developed by Watanabe\textsuperscript{22} in 2007. They placed cameras beside the hardstand to catch the attitudes of helicopter. The immediate images were transferred to monitoring station for computing the relating dynamics and assisting in landing. Even though the experimental results demonstrate the effectiveness of machine vision for the autonomous landing of helicopter, the developed scheme is not available for all kinds of situation. Once the cameras are not set up in the beginning, the helicopter would not be able to autonomously land in an arbitrary position.

Consequently, we propose to integrate the previous methods\textsuperscript{23-25} with image recognition technology for the autonomous navigation of hovercraft. The control center is implemented based on BASIC Stamp, which is easy for the design, high stability, and low price. According to the RoboRealm image recognition software, the hovercraft will be autonomously navigated to the assigned direction and destination.

**RC Hovercraft**

As be shown in Fig. 1, the operation principle of RC hovercraft is according to the fans which are installed on RC motors push the air down to the bottom of boat via ducts. Therefore, the boat could be propped up by the reacting force. The air cushion formed between the boat and the ground/water is used to averagely distribute the weight of boat to the bottom. Accordingly, the friction and the pressure of unit area could be decreased to the least. With the appropriate propellant system, the hovercraft has become a novel transportation with low resistance and high efficiency.

**Mathematical Model**

We assume that the output of downward motor is a constant, and the rotation rate of fan for controlling direction is an adjustable parameter. Based on the parameters represented in Fig. 2, we repeatedly do the simulation and correction to approach the mathematical model of RC hovercraft.

Accordingly, the dynamic equations are defined in Eqs (1)-(3).

\[ \dot{x} = \frac{\cos \alpha}{m} u_1 + d_1 \]  \hspace{1cm} (1)

\[ \dot{y} = \frac{\sin \alpha}{m} u_1 + d_2 \]  \hspace{1cm} (2)

\[ \dot{\alpha} = \frac{d \sin \beta}{I} u_2 + d_3 \]  \hspace{1cm} (3)

with \( u_1 = u_L + u_R \) and \( u_2 = u_L - u_R \). The \( u_L \) and \( u_R \) are the propulsive forces of left and right fans, respectively. \( d_1, d_2 \) and \( d_3 \) are unknown disturbances.

![Fig. 1 – A diagram of operation of RC hovercraft](image1)

![Fig. 2 – A two-dimension diagram of RC hovercraft](image2)
\(\alpha\) is an included angle between the central line of hovercraft and \(x\)-axis; \(\beta\) is an included angle between the center of gravity of hovercraft and the central line of left and right fans; \(d\) is the distance between the center of gravity of hovercraft and the central line of left and right fans; \(I\) is the rotation inertia; \(m\) is the total mass of hovercraft. Nevertheless, the values of above parameters are possibly changed of the shape and inner circuit of hovercraft.

**Fuzzy gain scheduled integral control**

Consider a nonlinear system is described by Eq. (4).

\[
\dot{x} = f(x, u) \\
y = x_1
\]

where \(f: \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}^n\) is a smooth function; \(x = x(t) = [x_1(t) \cdots x_n(t)]^T \in \mathbb{R}^n\); \(u = u(t) \in \mathbb{R}\). For tracking purpose, the fuzzy gain scheduled controller is designed to work as a gain scheduler on a reference state trajectory \(x^d(t)\). Suppose that \(x^d(t)\) is the value of the desired trajectory evaluated at a particular frozen time \(\tau\). Let \(u(t)=u_d\) be the corresponding input value at \(\tau\) such that \(f(x^d, u_d) = 0\). By setting \(x_\delta = x-x^d\), \(u_\delta = u-u_d\), we have

\[
\dot{x}_\delta = f(x, u) - f(x^d, u^d) = f(x_\delta + x^d, u_\delta + u_d) - f(x^d, u_d) \quad \cdots (5)
\]

The Lyapunov-linearized version of Eq. (4) about \((x^d, u^d)\) is

\[
\dot{x}_\delta = A(x^d, u^d) x_\delta + B(x^d, u^d) u_\delta \quad \cdots (6)
\]

where

\[
A(x^d, u^d) = \left( \frac{\partial f}{\partial x} \right)_{x=x^d, u=u^d} \\
B(x^d, u^d) = \left( \frac{\partial f}{\partial u} \right)_{x=x^d, u=u^d}
\]

The state feedback integral controller is of the form (Eq. (7))

\[
u_\delta = K_1(x^d, u^d) x_\delta + K_2(x^d, u^d) u_\delta \\
\sigma = x_1 - x^d_1
\]

where \(\sigma_\delta = \sigma - \sigma^d\) and \(\sigma^d = K_2^{-1}(u^d - K_1 x^d)\).

Applying the controller to the linear system (Eq. (6)) yields

\[
\begin{bmatrix}
\dot{x}_\delta \\
\sigma_\delta
\end{bmatrix} =
\begin{bmatrix}
A + BK_1 & BK_2 \\
C & 0
\end{bmatrix}
\begin{bmatrix}
x - x^d \\
\sigma_\delta
\end{bmatrix} \\
= A
\begin{bmatrix}
x - x^d \\
\sigma_\delta
\end{bmatrix} \quad \cdots (8)
\]

where \(C = [10 \cdots 0]^T\). Eigenvalues of \(A\) can be made to have negative real part provided the pair: \(A, B\) is controllable and

\[
\begin{bmatrix}
A & B \\
C & 0
\end{bmatrix} = n + 1 \quad \text{for all } \begin{bmatrix}
x^d \\
u^d
\end{bmatrix}.
\]

Clearly, the state feedback controller (Eq. (7)) provides a gain scheduling on the given desired trajectory \(x^d(t)\) if, however, a gain-scheduled controller is asked to be capable of tracking various slowly time varying signals, then the operating points in the state space have to be chosen carefully and the local gains designed at different operating points have to be interpolated to form an overall nonlinear control providing transitions between operation conditions. The fuzzy gain scheduled control, in effect, provides an efficient way of interpolation between the local gains.

Let \(x^d(=1 \cdots M)\) be the typical point in the \(i^\text{th}\) fuzzy region and let \(u_i\) be the corresponding constant input such that \(f(x^d, u_i) = 0\). Let \((x^d, u^d)\) be any intermediate operating point, that is, \(f(x^d, u^d) = 0\). The approximate local fuzzy model at this point can be described by the following fuzzy rules: \((i=1 \cdots M)\)

\[
R_i^j: \begin{cases}
\text{if } x^d = Lx^d_i \text{ then } \\
x = A(x^d - x^d_d) + B(u^d - u^d_d)
\end{cases} \quad \cdots (9)
\]

where \(Lx^d_i\) denotes the linguistic term of \(x^d\) in the \(i^\text{th}\) rule. Correspondingly, for \(i=1 \cdots M\), the fuzzy gain scheduled integral control law is described linguistically by Eq. (10),

\[
u_i^j: \begin{cases}
\text{if } x^d = Lx^d_j \text{ then } \\
u = K_1(x^d, u^d) \cdot (x - x^d) + K_2(x^d, u^d) \sigma_\delta + u^d
\end{cases} \quad \cdots (10)
\]

When the fuzzy controller (Eq. (10)) is applied to the fuzzy model (Eq. (9)), the closed-loop system can be described by Eq. (11),

\[
\dot{x} = \sum_{i} \sum_{j} \omega_i^j(x^d_i) \cdot \omega_i^j(x^d_d) \\
\left[\begin{array}{c}
\dot{x}_\delta \\
\dot{\sigma}_\delta
\end{array}\right] = \sum_{i} \sum_{j} \left[\begin{array}{c}
A \omega_i^j(x^d_d) - B \omega_i^j(x^d_d) \\
C \omega_i^j(x^d_d)
\end{array}\right] \\
\left[\begin{array}{c}
\dot{x}_\delta \\
\dot{\sigma}_\delta
\end{array}\right] = \sum_{i} \sum_{j} \left[\begin{array}{c}
A \omega_i^j(x^d_d) - B \omega_i^j(x^d_d) \\
C \omega_i^j(x^d_d)
\end{array}\right]
\]

Where

\[
\omega_i^j(x^d) = \frac{\mu_i^j(x^d)}{\sum \mu_i^j(x^d)} \\
\omega_i^j(x^d_d) = \frac{\mu_i^j(x^d_d)}{\sum \mu_i^j(x^d_d)}
\]
The detail derivation of fuzzy gain scheduled integral control design can be referred in literature\textsuperscript{10,26,27}.

**Architecture**

The configuration of designed hovercraft is displayed in Fig. 3. The mechanical parts of hovercraft are got from existing products. Otherwise, the motor, power supply, controller, and circuit are modified to fit our requirements. We install three DC motors in the middle and back of hovercraft. To avoid causing influence on other circuits while the middle motor is starting, the power of middle motor is separated from other powers. We use a specialized Li-type battery with 12 V and 7.2 A (maximum current) for providing DC power for motor. On the one hand the Basic Stamp and XBEE are used to be control and communication centers, and on the other hand the Webcam is used to detect the target during the navigation mode. The front view, lateral view and rear view of RC hovercraft are shown in Figs 4, 5, and 6, respectively.

**Remote control by BASIC stamp**

In the design of remote control for the hovercraft, we firstly implement the controlling program of motor by BASIC Stamp. Then with the integration of XBEE communication module, we can command the motor through the keys, W, A, S, D, and X, on the computer keyboard. The functional keys W, A, S, D and X are the commands of FORWARD, LEFT, STOP, RIGHT, and BACK for the motor. The flowchart of remote control procedure is illustrated in Fig. 7.
Autonomous navigation by image recognition technology

Based on the image recognition technology, we can achieve the autonomous navigation of RC hovercraft by means of RoboRealm. In the programming design, we divide a frame of 640x480 pixels into ten regions which are depicted in Fig. 8. If the target is detected within the “L” regions of frame, the hovercraft is navigated to the left forward direction. If the target is detected within the “R” regions of frame, the hovercraft is navigated to the right forward direction. If the target is detected within the “F” regions of frame, the hovercraft is navigated to the forward direction.

In the practical test, the displayed frames are demonstrated as Figs 9-11. When the target is detected by the recognition system, the controller will autonomously transfer the recognized data into command. Therefore, the hovercraft will navigate to the target according to the command. As be shown in Fig. 9, the target is detected on the middle position of frame, and a command “move w” is suggested for hovercraft to move forward. Similarly, the target is detected on the left and right positions of frame which are depicted in Figs 10 and 11, respectively. Accordingly, the commands “move a” and “move d” are provided for hovercraft to navigate to the left and right directions.

The flowchart of image recognition based navigation procedure is illustrated in Fig. 12. First, the
pre-filtering process will be performed before the target detection and image recognition. Once a target is detected by the Webcam, the caught image will be used to do the recognition. Then, the position of target on the frame will be determined. With the recognized decision, the controller will provide the relating command for hovercraft to move forward the target. With the cooperation of Webcam and controller, the hovercraft possesses the capability of target detection and image recognition. In addition, the hovercraft will automatically perform navigation until the target is arriving to the destination. Consequently, the developed hovercraft has the potential to carry out the surveillance tasks.

Results and Discussion

In the practical experiments, we utilize a situational mode to verify the effectiveness of the developed control methods for the hovercraft. The condition of situational mode is designed as shown in Fig. 13. The under part is beach, the upper part is ocean, and the lighthouse is regarded as target. The hovercraft is driven by remote control at beach, and is driven by autonomous navigation based on the image recognition at sea. First, the experimental results of remote control at beach are demonstrated in Figs 14-16. These results indicate that the hovercraft
could be successfully remote controlled toward the lighthouse. When the hovercraft is closed to the target, we manually switch the control mode to the autonomous navigation. Figures 17-19 indicate that the hovercraft is navigated to the lighthouse according to the detected positions of target. In Fig. 17, the lighthouse is recognized on the right side of frame, and the hovercraft is accordingly navigated to the right and forward direction. Similar, the lighthouse is recognized on the left side of frame as depicted in Fig. 18. The command is provided for the hovercraft to move right side. The actions of recognition and navigation are executed continuously until the hovercraft arrive the destination. As be shown in Fig. 19, the hovercraft based on the image recognition technology is successfully navigated to the target (lighthouse).

Conclusions

With the utilization of BASIC Stamp and XBEE communication module, we have successfully controlled the RC hovercraft and designed functional keys to easily issue the action commands. Moreover, the RoboRealm is used to provide the processing and recognition for the images which are caught by Webcam. The experimental results demonstrate that the autonomous navigation of RC hovercraft has been successfully performed based on image recognition technology.

References