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Stabilization of Non-holonomic 03 DOF Hovercraft using Robust RST Control Design

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Abstract:

There are several autonomous vehicles such that unmanned aerial vehicle (UAV), unmanned ground vehicle (UGV) and unmanned under-water vehicle (UUV). All these vehicles are proposed earlier for several applications. Researchers are still engaged in carrying out their research on hovercraft because of its hovering operation on land, water and ice. Moreover, due to this operation it has been significantly used in transporting the heavy loads from one place to another. Looking over its stability, power and size requirements, this paper proposes the stabilization of non-holonomic three degree of freedom (DOF) hovercraft using robust regulation and pole placement (RST) control design. This paper suggests dynamic controller design to stabilize the parameters of proposed prototype model of hovercraft. This control scheme enables our prototype to execute various tasks in dull, difficult, dangerous and dirty conditions. The paper proposes the Simulink based simulations to verify the results along with the validation with hardware results.

Keywords: *Non-holonomic, air cushion vehicle, dynamically controlling, RST (Regulation, Pole Placement & Tracking*

1. Introduction

The term 'under-actuated' or 'non-holonomic vehicles' both are same and are defined as an autonomous system that have a smaller number of actuators as compared to the degree of freedom. The paper addresses the hovering state problem of non-holonomic three degree of freedom hovercraft. At this state the number of forces and all torques should converge to zero as soon as possible so that the hovercraft can continuously hover at the surface. The discussed prototype in this paper is non-holonomic in nature because it has fewer control inputs than the degree of freedom. Its control inputs are thrust forces along yaw moment, surge direction while its degree of freedom is in x, y and in the mid of these axis.

In the proposed non-holonomic hovercraft, the most prominent problem is to develop a particular control scheme. This scheme may be further responsible to stabilize the proposed non-holonomic hovercraft as it is not satisfying the Roger Brockett's condition [1] of feedback control law that asymptotically stabilizing an equilibrium for proposed non-linear mechatronic system [2] and this is because of the sway that is produced indirectly by actuators. Although this is one of the problems of non-holonomic structures, one may find several control designs in order to control and stabilize the position, velocity and torque parameters of hovercraft model [3]. One may find various controller schemes so that some of them are proposed in order to analyse the driving operation of an under-actuated hovercraft on particularly trajectory [4] [5] in a smooth way using backstepping technique. Moreover, some have proposed continuous time varying tracking controller for non-holonomic surface vessel [6] and some focuses on both trajectory tracking and path planning [7] in order to operate the vehicle on provided reference trajectory. After a brief study of such non-holonomic structures one may get an idea of several control designs that have been implemented on wheeled mobile robots [8]. There are various actuated systems such that under, over and fully actuated systems but underactuated systems are difficult to stabilize. In this regard several control techniques like sliding mode controller (SMC) and dual proportional integral derivative (D-PID) had been proposed for controlling the two wheels of wheeled

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mobile robots (WMR) [2]. The most popular classical method suggested for non-holonomic structures is Regulation, pole-placement technique (RST) [9]. This paper proposes RST technique in order to analyse the hovering state of proposed non-holonomic hovercraft model at water and other surfaces.

It is obvious that any system's response may be affected by the external disturbances and for that purpose a non-linear observer technique [10] can be used. This technique not only estimates the external disturbance but also provide a way to reduce the disturbance error as well [11]. Furthermore, in our case these disturbances may vary frequently and are an obviously insufficient for robust stabilization. In order to reduce the effect of such disturbances one can use the estimators for dynamic coefficients (hydro-dynamic) [12] [13] using smooth projections. Nowadays, researcher prefers to implement hybrid control schemes in order to minimize the cons and maximize the pros. such that fuzzy based PID schemes [14]. These hybrid schemes can guarantee the stability as well as the bounded position error [15] but one may still face the singularity issues. After brief study of different algorithms it has been concluded that the machine learning based algorithms can eliminate this problem [16].

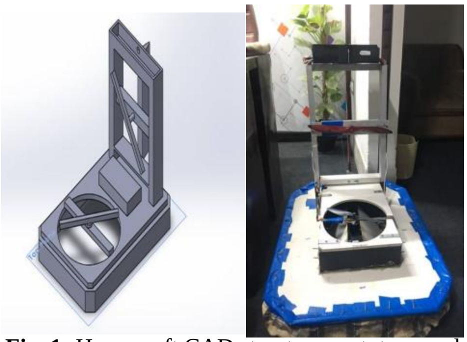

Fig. 1: Hovercraft CAD structure prototype and final

The main focus has been set on the deployment of an electronic circuit that can drive the proposed prototype precisely [17] as shown in figure 1. Moreover, in designing non-holonomic hovercraft the material of carbon fibre has been used in order to have less weight structure [18]. In all techniques proportional integral derivative (PID) is the easiest technique to implement and one may use fuzzy based PID technique to get much better results on such non-holonomic control system [19]. The proposed modelling and controlling work has been focused on hovercraft because of its significance in transporting heavy payload from one place to another by just calculating and controlling the inputs [20]. One may look for various control algorithms to stabilize any desired system but one should also look for the advantages as well as disadvantages of these techniques.

Discussing proportional integral derivative controller (PID), it is easy to implement and stabilize the system, whereas it may generate non-suitable settling time and may also amplify noise frequency in the proposed plant. Linear quadratic regulator controller (LQR) is proposed at the times to model the system in the presence of any external noise i.e. gaussian white noise. This controller may be problematic when the dimension of the system state is larger and this problem is more difficult to solve because it is no longer separable. In addition to this, one may study sliding mode control (SMC) [2] that has an ability to stabilize even a non-linear system which cannot be stabilized by continuous state feedback laws, but the only problem with it is its implementation i.e. actuators had to cope with the high frequency control actions that could produce premature wear and tear. Moreover, one also proposes the back stepping control design for autonomous vehicles because it is implemented through chain of integrators while produces some states of the system as virtual inputs even though it has no any effect on system.

2. Equation of motion

On a two-dimensional plane, the movement of hovercraft can be illustrated as in figure 2. The proposed model has two thrust propellers for the manveurability in 03 directions. This basically generates two forces as F_x and F_y along with the orientation (x, y, θ) of the hovercraft.

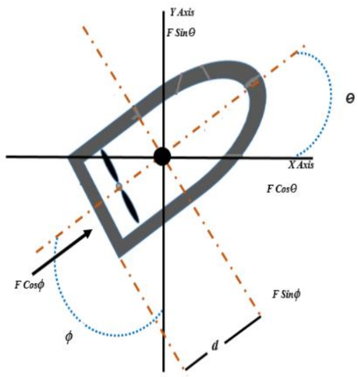

Fig. 2: Two-dimensional diagram for hovercraft model

Considering the above x-y plane, forces and observing the turning effect applied to hovercraft this paper presents the major six equations as mentioned below:

$$x = u \quad 1.1$$
$$y=v \quad 1.2$$
$$\theta= r \quad 1.3$$

Whereas, their derivatives are, as mentioned below:

$$u = \frac{Fcos\emptyset cos\theta - Fsin\emptyset cos\theta - bu}{m} \quad 1.4$$

$$v = \frac{Fcos\emptyset cos\theta + Fsin\emptyset cos\theta - bv}{m} \quad 1.5$$

$$r = \frac{dFsin\emptyset - br}{I} \quad 1.6$$

Hence the state space model can been developed using these six equations as shown below:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -b/m & 0 & 0 \\ 0 & 0 & 0 & 0 & -b/m & 0 \\ 0 & 0 & 0 & 0 & 0 & -b\theta/l \end{bmatrix} \begin{bmatrix} x \\ y \\ \theta \\ u \\ v \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/m & 0 \\ 0 & 1/m \\ 0 & d/l \end{bmatrix} \begin{bmatrix} Fx \\ Fy \end{bmatrix} \quad 1.7$$

$$C = [\ 1\ 1\ 1\ 0\ 0\ 0] \quad 1.8$$

$$D = [\ 0\ 0\ ] \quad 1.9$$

In the above equations the u, v are the linear velocities and r as angular velocity. Moreover, the b_v, b_u are the co-efficient of linear frictional force and b_r or $b\theta$ is the co-efficient of angular frictional force. In the state space matrix the m is the mass and l is given as the length of hovercraft respectively.

3. Control design

In order to get an optimal desired response from an actual response the RST controller has been proposed. It is obvious that any control system will never work for the same as it had been performing initially because of the variation in several parameters. This variation may occur due to several reasons such that temperature pressure conditions or simply by external disturbance (noise). Hence, one should look forward for a control design that may work on adaptive self-tuning of control systems. This paper proposes the technique named as regulation, pole-placement and tracking (RST) control design that is nothing but the placement of poles at right location.

RST or pole placement technique is the most widespread methodology used for advancing the control systems. Furthermore, if someone places feed forward controller along with feedback controller in order to manipulate the input in digital domain as well as reduces the noise or external disturbance, such technique is known as RST technique. The controller is based on the resolution of a Diophantine equation. In this heading, RST controller design is presented for the stabilization of non-holonomic hovercraft. Since RST technique is applied on discrete model hence the state space model will be turned into z-domain using the basic mathematics.

The transfer function of known system is,

$$G_p(q) = \frac{B(q)}{A(q)} \quad 2.0$$

Whereas the desired transfer function has been illustrated as,

$$G_m(q) = \frac{B_m(q)}{A_m(q)} \quad 2.1$$

RST based control algorithm provides fine results in stabilization the key response such that translational and rotational movement of hovercraft. By knowing the poles and zeros from the definition of transfer function paper proposes the below calculation and proposes the Diophantine equation:

$$Ru(t) = Tu_c(t) - Sy(t) \quad 2.2$$

Replacing S=T we get,

$$u(t) = \frac{T}{R}\left(u_c(t) - y(t)\right) = \frac{T}{R}\left(e(t)\right) \quad 2.3$$

Equation 2.3 represents the control law for controlling the desired parameters i.e., u, v and r (translational and angular velocities).

4. Simulation Results

Beneath this heading, one may look into the simulated control algorithm for non-holonomic hovercraft model using regulation and pole placement (RST) technique as illustrated in the figure 3.

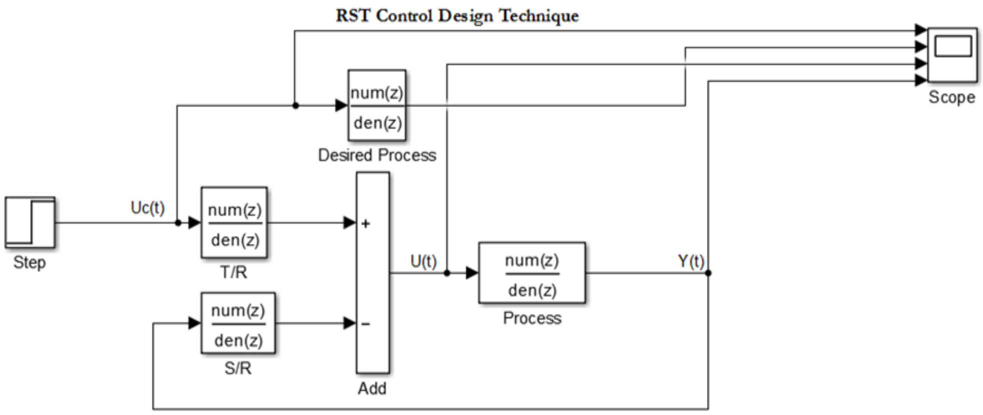

Fig. 3: Close loop (RST) based Control Diagram

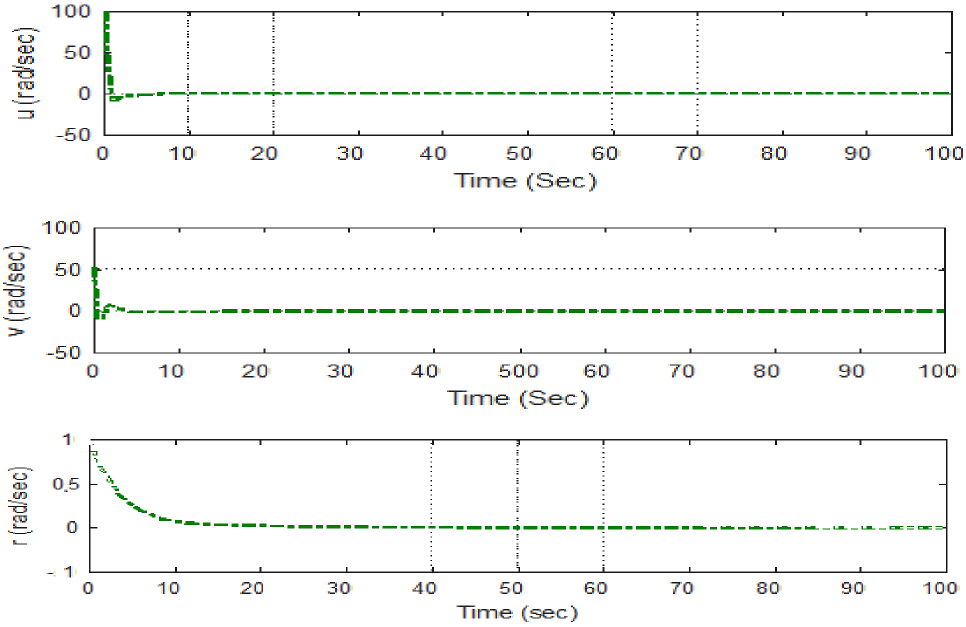

Fig. 4: Hovering state velocities u, v and r of proposed hovercraft

In the hovering state there would be two translational velocities and one rotational velocity namely *u*, *v* and *r*. The proposed RST control algorithm is designed to stabilize these velocities and converges it to zero state so that the hovercraft may contiuously hover on sea or any other surface.

The simulation results for all velocities are shown in figure 4. Moreover the torque (turning effect) produced during the rotational manevurability has been simulated at τ=0, 0.5 and 1 as illustrated in figure 5.

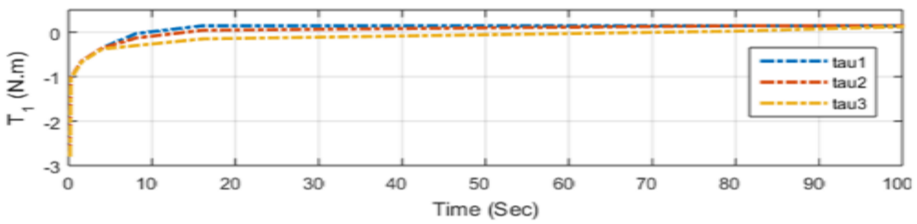

Fig. 5: The torque produced at different tau values

The feedback mechanism along with proposed control design shares the error being occurred while covering distance in x y and in the mid of these axis while turning as illustrated in figure 6:

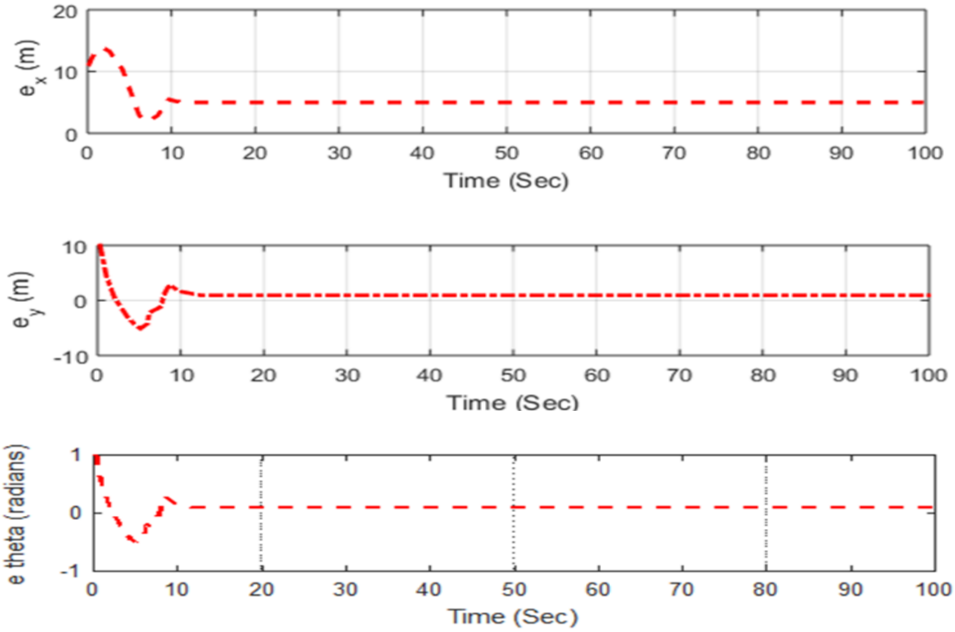

Fig. 6: The error signal produced with respct to u, v and r

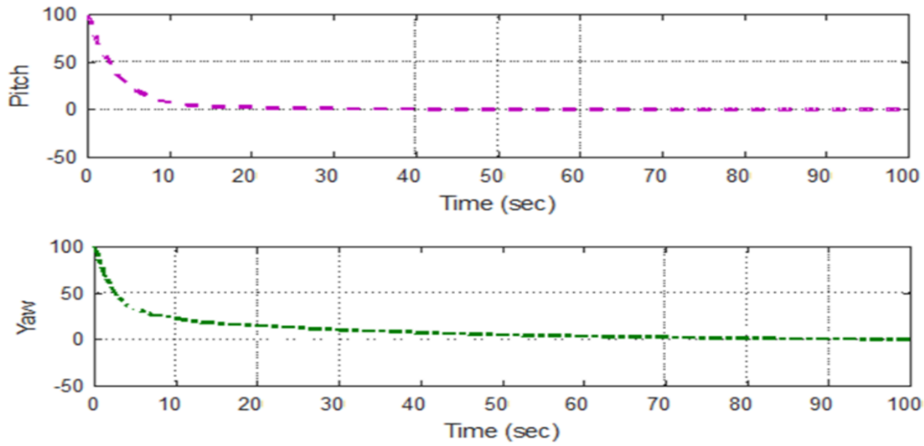

Fig. 7: Eular angles produced and simulated using Simulink

When proposed hovercraft is powered up, it will slightly go up from the front and at that moment the pitch is produced (rotation side to side) which is soon finished when the air in plenum settles or comes at equilibrium state. Moreover, rotation on vertical axis is known as yaw and this is produced when back fan along with rudder mechanism is powered up; the same settles at equilibrium state. It is noted that the rotation on front to back axis is known as roll that is not observed in this case as our ACV does not go in z-axis. The eular angles such that pitch and yaw are illustrated in figure 7.

5. Conclusion

In this paper robust RST controller is suggested to stabilize the non-holonomic 03 degree of freedom hovercraft model duly prepared in carbon fibre material. The technique not just controls the mathematically driven dynamics but also stabilizes the hovering state and three significant velocities and two Euler angles too. One may get all simulations and results being linked with each other. The best feature of the paper is the implementation of the algorithm at proposed model of nonholonomic hovercraft.

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