A survey on Backstepping Approach in Robotics

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***Abstract*— The world today is moving more towards robots that can replace/work with humans. Ex: Robotic vehicles, Humanoids, Medical robotics etc. Major challenge in robotics area is to understand the non-linear systems behavior. Backstepping is a systematic control design technique that aims to find linear approximations to nonlinear behavior (nonlinear system). This survey paper addresses few backstepping approaches and presents futuristic robot drone, an advanced form of underwater garbage collector.**

KeyWords: nonlinear systems, backstepping, Lyaponov function.

I. INTRODUCTION

Peter V.Kokotovic created the concept of Backstepping control in the early 1990s. As per Brian M. Borra (2012), "Backstepping is a recursive, control effort minimizing, constructive design procedure that interlaces the choice of a lyapunov function with the design of feedback control. It allows the use of certain plant states to act as intermediate, virtual controls, for breaking complex high order systems into a sequence of simpler lower-order design tasks." [1], [2].

The paper discusses below backstepping approaches:

a) The design and the simulation of a nonlinear controller for an aircraft.

b) Autonomous Mobile Robot Trajectory Tracking.

II. BACKSTEPPING APPROACH

A. The design and the simulation of a nonlinear controller for an aircraft

As the aircraft is a nonlinear system, controlling is achieved by moving the ailerons, elevator, rudder and the throttle. Only the elevator is dealt in this paper, as the throttle is constant, the ailerons and the rudder are null [1]. Refer Figure. 1.

For instance, if we have two identical aircrafts at different altitudes then higher the altitude smaller is the airflow, the friction on the wings, the drag and much smaller is airspeed. Thus, flight path angle will be different due to direct dependency on the airspeed.

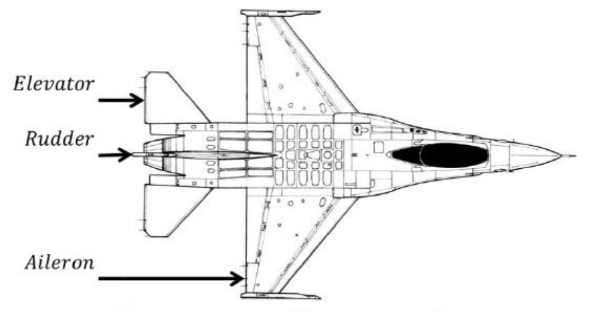


Fig. 1. Actuators: Rudder, Elevator, Aileron

To simply nonlinear aircraft:

a) Classical method controller is designed on linear control theory, this technique uses a multiple modelling approach.The most well known methods are PID, gain-scheduled and nested saturation. These methods can be completed with a neural network technique.

b) A single controller method is used due to nonlinear equations of motion.In this method the aircraft is stabilized regaradless of altitude, the speed and temperature. The most well known nonlinear aircraft dynamics control methods are feedback linearzation, backstepping and slide mode control. Backstepping is discussed for the nonlinear aircraft system.

The paper discusses equations of motion and the equations to express elevator deflection δ_e. The three main variables used for the backstepping method are γ, α, Q [1].
The pitch aerodynamic coefficient is:

$$C_M = C_{M_O}(\alpha,\beta) + C_{M_q}(\alpha)\frac{c}{2V}Q + C_{M_{\delta_e}}(\alpha)\delta_e \tag{1}$$

The pitch moment is [1]:

$$M = \overline{q}ScC_M \tag{2}$$

The derivative of pitch rate is [1]:

$$\dot{Q} = (c_5P - c_7M_T)R - c_6(P^2 - R^2) + c_7M \tag{3}$$

The derivative of angle of attack is [1]:

$$\dot{\alpha} = \frac{-Lift}{mVcos\beta} + \frac{1}{mVcos\beta}(-Tsin\alpha + mgcos\gamma cos\mu) + Q - tan\beta(Pcos\alpha + Rsin\alpha) \tag{4}$$

The derivative of flight path angle is [1]:

$$\gamma = \frac{sin\mu}{mV}(-Dsin\beta - Ycos\beta) + \frac{1}{mV}(Tcos\alpha sin\beta sin\mu - mgcos\gamma) + \frac{cos\mu}{mV}(Lift + Tsin\alpha) \tag{5}$$

Controller design for the flight path angle:

Figure 2. shows the process to find elevator expression that corresponds to the desired flight path angle. The approach is to create an error and derivative to zero it out [1].

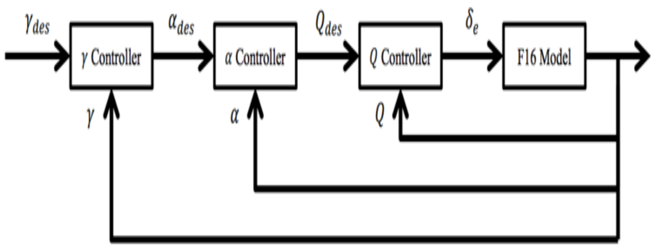


Fig. 2. Controller block diagram

Lyapunov function candidate is defined to stabilize the system and Hence, the system is proved to be stable as its derivative is negative definite.
After solving the equations,
The desired elevator deflection is:

$$\delta_e = \frac{\dot{Q}_{des} - k_Q e_Q - f_P(\gamma,\alpha,Q) - e_\alpha}{g_P(\gamma,\alpha,Q)} \tag{6}$$

RESULTS

The simulation duration time in Figure 3 is 30s. Figure 3.a shows the desired value, identified with stars and the real value that follows the reference signal. The flight path angle oscillates the first two seconds, then takes 5seconds to reach the 5^o degrees, and finally takes 5 seconds to return to 0^o. Changes in the flight path angle leads to changes in angle of attack (figure 3.b) that modifications in the pitch rate (figure 3.c). To follow the desired flight path angle, the elevator deflection (figure 3.d) oscillates the first two seconds, deflects to the bottom at 10seconds, and deflects to the top at 12seconds [1].

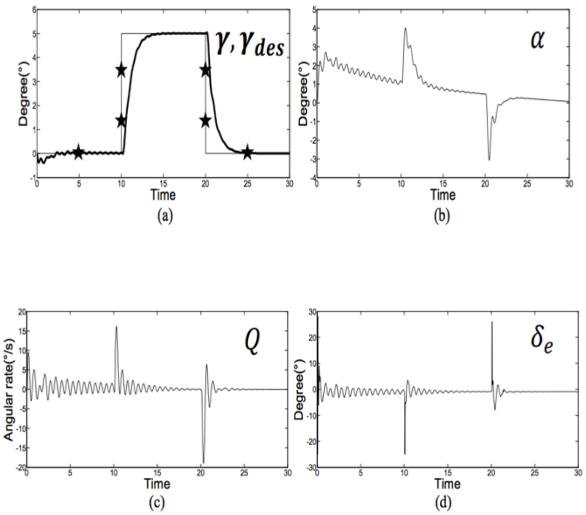


Fig. 3. (a) Flight path angle and desired path angle, (b)Angle of attack,(c)Pitch rate, (d) elevator deflection.

B. *Autonomous Mobile Robot Trajectory Tracking*

The paper proposes a backstepping controller design for trajectory tracking of unicycle-type mobile robots [3]. Dynamic model of unicycle-like mobile is presented and the kinetic controller, which is based on the robot kinematics, is introduced to generate the desired linear and angular velocities for given trajectory. Lyapunov theory proves its stability property.

The Dynamic model of unicycle-like robot model is discussed [3],[4]:

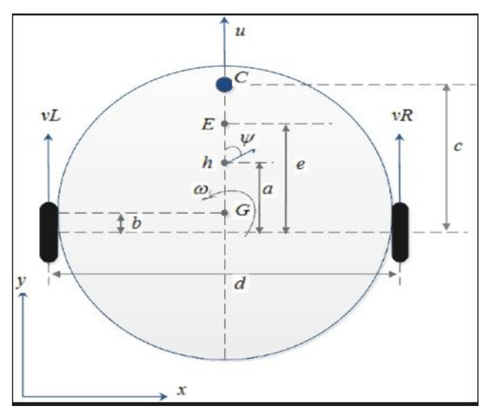


Fig. 4. The unicycle-like mobile robot

Figure 4. Illustrates the mobile robot.
Where, G is the center of mass of the robot, C is the position of the castor wheel, E is the location of a tool onboard the robot, h is the point of interest with coordinates x and y in the XY plane, ψ is the robot orientation, and *a* is the distance between the point of the interest and the central point of the

virtual axis linking the traction wheels (point B), u and ω are the linear and angular velocities of the robot.
Therefore, the states of mobile robot can be obtained as [3], [4]:

$$\begin{pmatrix}\dot{x}\\ \dot{y}\\ \dot{\psi}\\ \dot{u}\\ \dot{\omega}\end{pmatrix}=\begin{pmatrix}(u\cos(\psi)-a\omega\sin(\psi))\\ (u\sin(\psi)+a\omega\cos(\psi))\\ \omega\\ \frac{\lambda_3}{\lambda_1}\omega^2-\frac{\lambda_4}{\lambda_1}u\\ -\frac{\lambda_5}{\lambda_2}u\omega-\frac{\lambda_6}{\lambda_2}\omega\end{pmatrix}+\begin{pmatrix}0&0\\0&0\\0&0\\ \frac{1}{\lambda_1}&0\\ \frac{1}{\lambda_2}&0\end{pmatrix}\begin{pmatrix}u_{ref}\\ \omega_{ref}\end{pmatrix}\quad(7)$$

The parameters of dynamic model are: λ_i, i=1….,6 and defined as follows: [3]

$$\begin{cases}\lambda_1=\dfrac{\frac{R_a}{k_a}(mR_tr+2I_e)+2rk_{DT}}{(2rk_{PT})}\\ \lambda_2=\dfrac{\frac{R_a}{k_a}(I_ed^2+2R_tr(I_z+mb^2))+2rdk_{DR}}{(2rdk_{PR})}\\ \lambda_3=\dfrac{R_a}{k_a}\dfrac{mbR_t}{2k_{PT}}\\ \lambda_4=\dfrac{\frac{R_a}{k_a}(\frac{k_ak_b}{R_a}+B_e)}{(rk_{PT})}+1\\ \lambda_5=\dfrac{R_a}{k_a}\dfrac{mbR_t}{2k_{PR}}\\ \lambda_6=\dfrac{\frac{R_a}{k_a}(\frac{k_ak_b}{R_a}+B_e)d}{(rk_{PR})}+1\end{cases}\quad(8)$$

The paper presents two different types of controllers:
Kinetic controller for external loop and a backstepping controller for an internal loop as see in figure 5. [3].

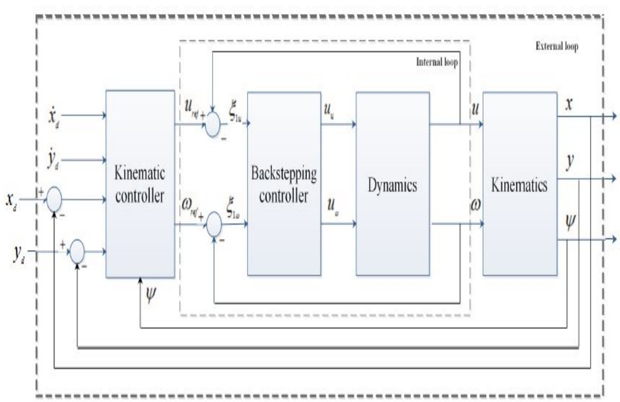


Fig. 5. The unicycle-like mobile robot

a) *Kinetic controller:*

The kinetic equations of mobile robot in figure 4: are described by [3]

$$\begin{pmatrix}\dot{x}\\ \dot{y}\end{pmatrix}=c\begin{pmatrix}u_{ref}\\ \omega_{ref}\end{pmatrix}\quad(9)$$

$$A=\begin{pmatrix}u\cos(\psi) & -a\omega\sin(\psi)\\ \sin(\psi) & a\omega\cos(\psi)\end{pmatrix}\quad(10)$$

Thus, control law gives u_{ref} ω_{ref} with current position errors ξ_x and ξ_y.

To satisfy the Lyapunov candiate function,

$$\dot{V_\xi}=\begin{cases}\{-\xi_x^T\xi_x<0\\ -\xi_x^T\xi_y<0\end{cases}\text{(Εδουαρδ Φινοκι, 2015)}\quad(11)$$

which is negative definite.
Clearly, if ξ goes to zero then h converges to h_d and the tracking error is asymptotically stable.

b) *Backstepping Controller:*

The backstepping control is used to design the controller which is making error dynamics stable [3], [5], [6]. The design of backstepping controller is based on Lyapunov theorem, the objective of this technique is to determine a control law that provides system stability. The dynamic part of equation (5) is:

$$\begin{cases}\dot{u}=\frac{\lambda_3}{\lambda_1}\omega^2-\frac{\lambda_4}{\lambda_1}u+\frac{u_{ref}}{\lambda_1}\\ \dot{\omega}=\frac{\lambda_5}{\lambda_2}u\omega-\frac{\lambda_6}{\lambda_2}\omega+\frac{\omega_{ref}}{\lambda_2}\end{cases}\quad(12)$$

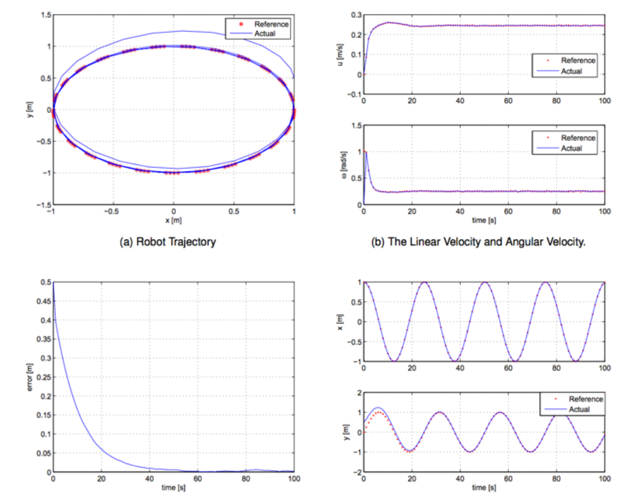
To prove the asymptotic stability of the tracking trajectory of wheeled mobile robot [3].

$$\begin{cases}\dot{V}(\xi_{1u},\xi_{2u})=-K_{1u}\xi_{1u}^2-K_{2u}\xi_{2u}^2<0\\ \dot{V}(\xi_{1\omega},\xi_{2\omega})=-K_{1\omega}\xi_{1\omega}^2-K_{2\omega}\xi_{2\omega}^2<0\end{cases}\quad(13)$$

Therefore, V along the trajectories is negative definite.

RESULTS

The experimental results for backstepping controller are shown below [3]. The task for a mobile robot is to follow a circular trajectory but the robot follows the reference trajectory with small error in figure 6a. At t=20s, it can be seen in figure 6c that the distance error begins to increase with time and tends to zero. The robot velocities v and ω are plotted in figure 6b. From figure 6d, robot arrives at the end of the reference trajectory and catches up to the desired coordinates.



(a) Robot Trajectory

(b) The Linear Velocity and Angular Velocity.

(c) Distance errors for experiments.

(d) Time evolution of current and the desired coordinates. .

Fig. 6. Experimental Results

III. Conclusion

In this paper, the backstepping method is applied to control flight path angle and a review of the kinematics and dynamics of a differential drive wheeled mobile robot and design of a controller for a unicycle-like mobile robot. Though, all related papers are not described in detail, the important ideas to the research path are revived.

IV. Proposal for Futuriestic Robot

A futuristic Garbage Robot Drone Proposal using Bac-stepping and sliding mode Control Methods could be created within 20years that would use a particle beam (like Cern's Particle beam) to disassemble trash at the quantum level. This would produce a viable energy source wherein energy companies would benefit and environmentalist would be satisfied. The Robot would search the ocean floor for anomalies such as dumped radioactive waste, plastics, etc. The robot will then try to match objects it finds to see database (fish, coral etc.). It would proceed to catch the deemed trash in a cylinder tube and net and use an energy beam to dissemble the materials into energy via Einstein's energy mass conversion. The initial power would be sustained by subsequent beam projections on matter turning into energy. A futuristic use for robotics of this sort would be to occupy the sea and clean the oceans that are littered with all sorts of debris contributing to pollution of water and the death of sea life. A device like this, which would catch the trash but not transfer it into energy can be found in the article where the inventor Ahoyi says, "Along with cleaning the oceans, the trash drone could yield profits for companies seeking to reduce petroleum use and recycle plastics [7]." This type of robot will be of great benefit to the earth and future generations.

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