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Robust model predictive control of the automatic operation boats for aquaculture

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ABSTRACT

This paper proposes a robust model predictive control (RMPC) approach for the automatic operation boats to cast baits evenly along desired paths. The difficulties in the control design come from the control system model, which is nonlinear, underactuated, input saturated, and disturbed by time-varying signals. The RMPC overcomes these difficulties by the receding horizon optimization explicitly considering the input saturation and using the mixed H_2/H_∞ cost function. To decrease computational complexity of the RMPC, a polyhedral model is constructed as the predictive model based on dynamics of the path-following error. The feasibility and effectiveness of the proposed path-following control is verified by theoretical analysis and illustrated by simulations and experiments.

1. Introduction

In aquaculture, weeding timely and casting baits evenly are important for crab farming, since rotten weeds deteriorate water quality and uneven baits affect crab production. Traditional artificial ways in weeding and casting baits have the problems of high labor costs and low efficiency. Recently, automatic operation boats (AOBs) have been considered as effective tools to simultaneously weeding and casting bait evenly along desired paths (Ge, 2010; Hu et al., 2015; Liu et al., 2014). Thus, path-following control for the operation boats has gained more and more attentions. S-shaped paths have been considered as reference trajectories for the AOBs to realize full coverage of fish/crab ponds. The S-shaped paths can be decomposed into piecewise straight lines with zero curvature. Even if the desired paths have non-zero curvature, they are often possible to be considered as many piecewise straight lines approximately (Ler et al., 2003). Thus, straight line path following is the main control objective for the AOB.

The AOBs for aquaculture usually sail in small sized ponds at low speeds. Compared with traditional boats, control of the AOB for aquaculture has more difficulties, which are stated as follows:

(1) The AOBs for aquaculture are actuated by paddle wheels. Compared with steering engines-based and propellers-based actuations, paddle wheels-based actuations have the advantages of small rotation radiuses and weeds winding prevention. The number of control variables for the AOBs is one, which is smaller than three, the number of degree of systems freedom. Thus, the control systems of the AOBs are underactuated (Fossen, 2012). Traditional vectors-based control for general motion systems cannot be used for the underactuated dynamics effectively (Li et al., 2009), high-gain control cannot be applied for AOBs either, due to the low control efficiency of paddle wheels (Ashrafiuon et al., 2010).
(2) In the AOBs, the baits for crabs are thrown by centrifugal forces from the rotating disk on the boat feeding machine. Then, the reaction from the centrifugal forces to the boat can be considered as system disturbances to the control system. Since amplitude and width of the thrown baits are closely related to species, growth periods, and farming density of the crabs, the reaction force and the system disturbances are time-varying signals. Meanwhile, the violent vibration of the electric motors brings more exogenous disturbances to the boat dynamics. Thus, the time-varying disturbances severely affect tracking accuracy and stability of the closed-loop control system. How to restrain the time-varying disturbances is important for control of the AOBs (Yang et al., 2014).
(3) To avoid collision to the pond embankment, the turning radius of the boat should be kept as small as possible. This possibly leads to control saturation of the AOBs due to their bad maneuverability and low efficiency of paddle wheels in

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shallow water. Ignoring the control saturation may result in degrading of path following, instability of the closed-loop control system and even disasters (Huang et al., 2015). Thus, input saturation must be taken into consideration in control of the AOBs.

Based on the above analysis, control of the AOBs for aquaculture must take input saturation, time-varying disturbances and under-actuated dynamics into consideration. Path-following control of the AOBs for aquaculture is still in the bud and very few result on it has been obtained. In Zhao et al. (2016), a fuzzy PD control scheme is designed for the AOB to follow straight paths without considering the time-varying disturbances and the input saturation, which severely affects the control performance. Therefore, control of the AOBs for aquaculture deserves more studies.

Model predictive control (MPC) (Sun et al., 2017; Zhang et al., in press; Zhang and Sun, 2016) has been considered as an effective approach and applied for many surface vessels to follow desired paths (Ghaemi et al., 2010; Oh and Sun, 2010; Zheng et al., 2016; Li et al., 2009; Li and Sun, 2012), for its ability in handling system constraints actively in receding horizon optimization. But no system disturbance was considered in Ghaemi et al. (2010), Oh and Sun (2010), Zheng et al. (2016), Li et al. (2009), and thus the proposed MPC in Ghaemi et al. (2010), Oh and Sun (2010), Zheng et al. (2016), Li et al. (2009) lacks robustness to strong system disturbances. Current research shows that strong time-varying disturbances or severe plant uncertainties cannot be restrained or compensated directly and promptly based on MPC with nominal model. Therefore, it is necessary to design new RMPC to improve robustness of AOBs control to the strong time-varying disturbances. In Li and Sun (2012), Z. Li and J. Sun proposed a RMPC strategy for unmanned surface vessels to do course keeping. In Li and Sun (2012), a Taylor linearization based linear model is chosen as the predictive model under the assumption that the disturbances changes slowly with time and the disturbance at time step k can be compensated feedforwardly by the disturbance estimation at time step $k-1$. The RMPC is a breakthrough to control of surface vessels, but it has the following deficiencies: (1) the Taylor linearization brings much more uncertainties and more difficulties to RMPC of the vessels; (2) one-step prediction is used in the RMPC and no terminal constraints is presented in it, which brings difficulties in stability analysis of the closed-loop control system. Therefore, current MPC for surface vessels (Ghaemi et al., 2010; Oh and Sun, 2010; Zheng et al., 2016; Li et al., 2009; Li and Sun, 2012) cant solve the control problem of the AOBs for aquaculture.

In this paper, a H_2/H_∞ RMPC approach is proposed for the AOBs to evenly cast baits along desired paths. In the RMPC, a mixed H_2/H_∞ cost function is used to improve control robustness, a polyhedral model is constructed as the predictive model to decrease computational complexity of MPC and the input saturation is tackled by explicitly considering it in the receding horizon optimization. The advantages of H_2/H_∞ and MPC in robustness and tackling constraints are fully exploited in the proposed RMPC (Kalmaria et al., 2014; Patience and Orukpe, 2007). Obviously, the proposed control overcomes the three difficulties in control design discussed above.

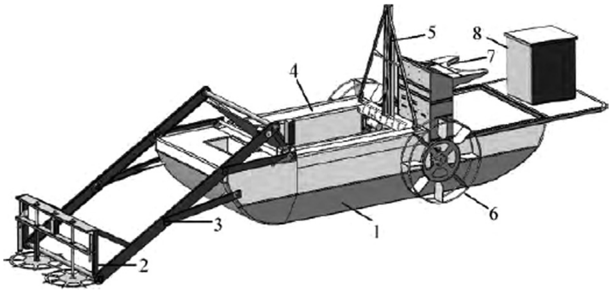

Fig. 1. The structure diagram of operation boat (1. the hull; 2. the cutting device for aquatic weeds; 3. the conveying device for aquatic weeds; 4. the collection box for aquatic weeds; 5. the aquatic weeds paving device; 6. the paddle wheel; 7. the operation station; 8. the feeding machine.)

Table 1
Main parameters.

Parameters	Values
Hull size (LWH)/m	4.0 × 1.6 × 1.2
Navigation velocity/$\mathrm{m \cdot s^{-1}}$	0–2
No-load depth/m	0.35
No-load displacement/$\mathrm{m^3}$	1.6
Maximum load/kg	500
Cutting angular velocity/$\mathrm{rad \cdot s^{-1}}$	0–6.2
Conveying velocity/$\mathrm{m \cdot s^{-1}}$	0–1
Cutting depth range/m	0–0.6
Feeding velocity/$\mathrm{kg \cdot h^{-1}}$	100

The organization of this paper is stated as follows. Section 2 presents the general structure of the agriculture operation boat (AOB). Section 3 presents the dynamics of the path-following errors. In Section 4, we design the proposed RMPC. Simulations and experiments are described in Sections 5 and 6, respectively. At last, Section 7 makes conclusions of the whole paper.

2. General structure of the agricultural operation boat

The AOB mainly consists of the hull, the aquatic weed clearing device, the feeding machine, and the paddle wheel driving device, whose structure diagram and main parameters are shown in Fig. 1 and Table 1, respectively. In Fig. 1, the cutting and conveying devices placed on the bow can cut and collect aquatic weeds, the collection box in the middle of the hull can store cut weeds; the paving device behind the collection box can pave aquatic weeds and avoid the accumulation, and the feeding machine in the stern can cast baits. The paddle wheels equipped on both sides of the hull is the driving device, which can avoid weeds winding. Electricity of the whole system is supplied by a 48 V lithium battery with 120AH capacity, which has the advantages of no pollution, high efficiency, and low noises.

3. Dynamics of path-following errors

Fig. 2 presents the baits casting trajectory, which completely covers the given crab pond. The trajectory mainly determines two basic movements: straight line path following and spot turning. To save time, shorten the distance and reduce fuel consumption, the routes between turning points are approximated by straight rhumb lines (Li et al., 2009). Thus, straight line path following is the main objectives of the control system.

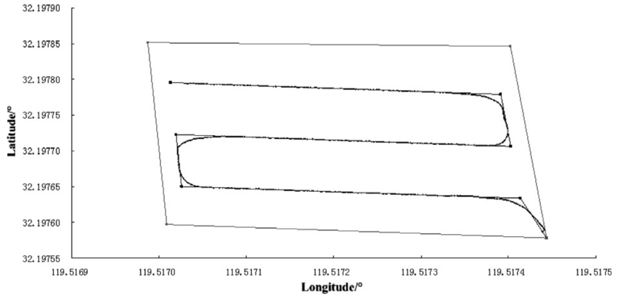

Fig. 2. The baits casting trajectory.