

SIMULATION OF SHIP'S HULL UNDERWATER CLEANING ROBOT

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Abstract: *The aim of the work is mathematical description and simulation of an underwater robot, which is meant for cleaning off the outgrowth from ship hulls. The task of mathematical simulation involves defining in differential terms all the variables considered: driving torque of the DC motors used for driving the caterpillars, which is a function of motor current and, consequently, input voltage; inertial characteristics of the robot; frictional and environmental resistance forces, out of which resultant motion parameters – position, velocity and acceleration – of the robot can be expressed.*
Key words: ship, cleaning device, motion control, robot

1. PROBLEM STATEMENT

The first task of the simulation is describing the working environment for the robot and the resultant forces that interact with the robot during its working time. The main peculiarities of the working environment for the robot are the levels of slope for the robot and the aquatic medium. The slope for the robot may include any angle between 90^0 and 180^0 . This means that provisions have to be made to endow a constant attraction force between the robot and the ship's hull. Working in the aquatic environment, in its part, means extra viscous damping forces proportional to the velocity of the robot and the force of Archimedes, which acts against the gravitational force. The primary source of resistance forces, though, is the destroyable

medium of outgrowth, which is to be described as well.

Another task of the simulation is to choose the types of motions and control principles, both in the sense of path to be followed and the velocities and accelerations to be chosen, which would be of practical importance.

2. APPLICATION AREA

Application area, as implied in the paper title, is large size ship hull cleaning which is particularly important in Mediterranean climate seas where the outgrowth layer thickness reaches size of tens of cm annually. With the help of the robot this task could be automated making use of a remote control system.

3. RESEARCH COURSE

The research course includes expression of all the acting factors in mathematical terms, linking them in a form of differential equations thus providing an opportunity of evaluating the responses of the system in dynamic continuous time mode. According to the analysis of the reduced differential system simulation results the best motion control algorithm could be chosen.

3.1 Destroyable medium

Destroyable medium based on [1] is assumed to be consisting of two upper layers of various densities providing viscous resistance forces and the bottom layer providing dry static and kinetic

friction resistance forces, which, according to [1], can be overcome by robot's blade vibrations produced by electric magnet.

3.2 Attraction forces

For determining the minimum attraction forces that are to be provided, the ultimate situations have to be considered which are when the robot is moving along a vertical wall or upside down. These situations are shown in Fig. 1, where

- F_a – attraction force,
- F_{stf} – force of static friction,
- F_A – force of Archimedes,
- F_{Oy}, F_{Ox} – resistance force components,
- G – gravitation force,
- M_T – driving torque.

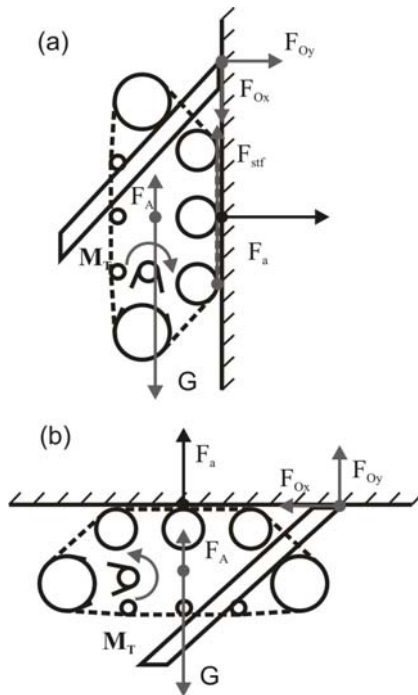


Fig. 1. Attraction force calculation schemes

As a solution for providing the necessary attraction force, caterpillars with built-in permanent magnets have been chosen [1]. The magnets provide a presumably uniform distribution of attraction force q_m which can be simplified as a concentrated force F_m producing a corresponding normal reaction N [2]. The minimum required force can be found from the following general equations for (a) and (b) cases respectively:

$$F_a = (G + F_{Ox} - F_A)/k_{st} - F_{Oy} \quad (1)$$

where k_{st} – coefficient of static friction,

$$F_a = \frac{F_{Ox}}{k_{st}} + G - F_A - F_{Oy} \quad (2)$$

The F_{Ox} component has to be compensated by traction force produced by M_T , as skidding otherwise occurs (which is the moment when electric magnet [1] is activated). Thus only the F_{Oy} component is of importance. It has to be considered, though, that the normal reaction force has to produce static friction force greater than minimum as extra friction is necessary in order to provide robot's motion. A condition that has to be fulfilled is that the magnets mustn't exceed a certain distance from the hull, as the magnetic force decrease in relation to the clearance distance is not linear. Practically it would mean that the robot should always be placed on surfaces already clean from outgrowth.

3.3 Factors acting on a single track

For calculations, the actual model (see Fig. 2 (a)) of the robot is simplified in two steps. In the first step, all the moments and forces on each axis (designated as axis i) are reduced to a resultant viscous damping coefficient $b_{red i}$ and a resultant dry resistance moment $M_{red f i}$ [3]. A resultant moment of inertia $I_{red i}$ for each axis is also computed. Moment of inertia for the whole robot (in the side plane) is assumed to be acting on the axis, which are in contact with the hull surface. The driving torque M_T is assumed to be acting on the first axis, whereas the outgrowth resistance moments, resulting from all outgrowth layers, are assumed to be acting on the axis, which are in direct contact with the hull surface. In the second step a final reduction is done deriving a single axis model (see Fig. 2 (b)) with resultant parameters b_{red} , $M_{red f}$ and I_{red} , which are calculated for the first, i.e., motor axis.

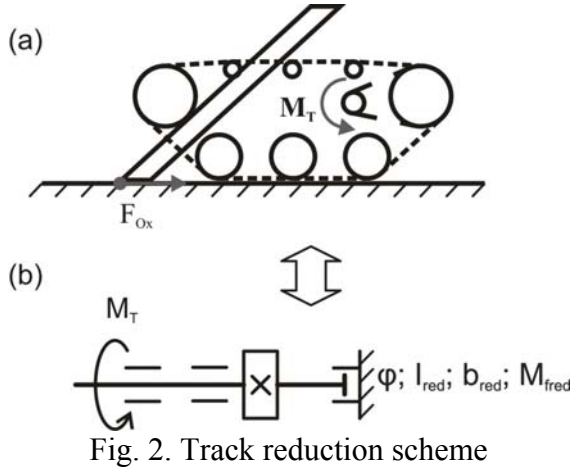


Fig. 2. Track reduction scheme

3.4 Reduction of the robot

From the acquired track model a reduced model of the robot is derived in two steps (see Fig. 3). In the first step a model is derived, which includes only resultant forces acting on each track [3]. In this case the robot is considered as a mechanical system consisting of two parallel forces with a rigid link between them – geometrically it resembles a view from above. With a DC motor chosen as the driving torque provider for each track separately, derivation is based on the following equations [4]:

$$L\dot{i} = U - Ri - k_e\dot{\varphi} \quad (3)$$

$$I_{red}\ddot{\varphi} = k_t i - b_{red}\dot{\varphi} - M_{fred} \quad (4)$$

where

L – electric inductance,

i – motor current,

φ – motor axis rotation angle,

U – motor voltage,

R – motor electric resistance,

k_e, k_t – electromotive force constants.

From equations (3) and (4) with the help of a reduced wheel radius R an equivalent track force can be computed [3]:

$$F_i = \frac{I_{red}\ddot{\varphi}}{R} \quad (5)$$

In the second step a model is derived, in which forces of both tracks are transferred to the mass centre of robot, which is assumed by default to be in the centre of the rigid link [3]. As a result, a resultant force F_{res} is computed and corresponding moments are added to the scheme:

$$F_{res} = F_1 + F_2 \quad (6)$$

$$M_{res} = 0.5 \cdot (F_2 - F_1) \cdot l - M_{swf} \quad (7)$$

where

F_1, F_2 – active forces on both tracks,

M_{swf} – swerving friction moment,

l – distance between tracks.

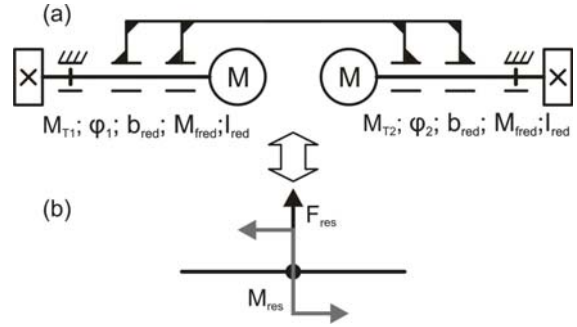


Fig. 3. Robot reduction scheme

3.5 Water resistance

The model of the robot derived above is incomplete without considering the water resistance forces that act on the whole surface of the robot as it moves [2]. Water resistance may differ considerably depending on the design of the robot's outer surfaces. Two motion cases should be distinguished here which are rectilinear motion and swerving motion (the rotational velocity in this case should be calculated for the mass centre as the final force reduction has been done for this point). The motion separation is based on the assumption that in the first case the whole surface of the robot (except for the caterpillars) has the same velocity of motion, whereas in the second case the linear velocity of every point on the surface is proportional to the distance from the rotation centre. As a solution to these cases an experimental estimation of viscous damping coefficients b_{rec} and b_{rot} for each case separately can be done [2]. Finally, a combined motion should be considered. In this case both velocities should be separated in order to apply the appropriate coefficients. That actually has been done already by computing the resultant force and moment for the mass centre. Thus final resultant forces and moments can be computed after the following equations:

$$F = F_{res} - \frac{b_{rec}}{m} \cdot \int F \cdot dt \quad (8)$$

where

m – mass of robot,

$$M = M_{res} - \frac{b_{rot}}{I_O} \cdot \int M \cdot dt \quad (9)$$

where

I_O – robot's moment of inertia, calculated in horizontal (top) plane for the centre of mass.

3.6 Track blocking

Special attention should be paid to the situation, when one of the tracks is blocked, e.g., by brake. In this case rotation on the middle point axes of the blocked track is possible if the resultant force doesn't exceed the static friction force of the blocked track [2]:

$$F \leq R_{st} \quad (10)$$

The corresponding moment is:

$$M_{res} = F \cdot l - \text{sign}(F) \cdot M_{swf} \quad (11)$$

where

M_{swf} - friction force moment.

3.7 Principles of robot motion control

For motion control, cases of practical importance are to be considered. First it should be noted that motion control is more relevant to starting and preserving the motion, as stopping the motion is mainly dependent on the efficiency of the brakes used (together with water resistance forces) provided that some anti-slippage system like periodic braking is in used. The basic motion types include: rectilinear motion, rotation on the mass centre axes (rotation radius 0), rotation on a track middle point axes (rotation radius $0.5l$). As a common condition for all motion cases is the necessity for track forces not to exceed the resultant static friction force [2], as otherwise slippage may occur:

$$F_{1;2} \leq R_{st} \quad (12)$$

Thus the electric magnet [1] is activated when resistance forces exceed R_{st} . Equation (12) is written bearing in mind that the track forces are included in the resultant differential equations (8) and (9) and thus incorporate the influence of water

resistance forces. For practical purposes it is assumed that an average value of R_{st} could be used, as this generally might be the case for surfaces already clean from outgrowth on which the robot is supposed to be standing on (see 3.2).

– Rectilinear motion

Referring to equation (7), it can be concluded that for accomplishment of this motion both track forces have to be equal as the resultant moment M becomes equal to 0 then and only resultant force F is acting on the mass centre.

– Rotation on the mass centre axes

For accomplishment of this motion both track forces have to be equal by magnitude and opposite by direction, as then the resultant force F is equal to 0 and only the resultant moment M is acting on the mass centre.

– Rotation on a track middle point axes

For accomplishment of this motion a general scheme should be considered. This scheme is based on the principle of expressing the angular acceleration of the motion in two ways – in relation to the resultant force F and in relation to the resultant moment M – and consequently unifying both equations:

$$\ddot{\alpha} = \frac{F}{m \cdot r} \quad (13)$$

where

$\ddot{\alpha}$ – angular acceleration,

r – radius of the rotation motion, measured for the mass centre.

$$\ddot{\alpha} = \frac{M}{I_O + m \cdot r} \quad (14)$$

$$\frac{F}{m \cdot r} = \frac{M}{I_O + m \cdot r} \quad (15)$$

Out of the equation (15) a differential relation between the track forces can be established:

$$F_2 = f(F_1) \quad (16)$$

If the driving voltage U_2 is expressed out of F_2 then a differential control system can be established in order to attain a rotary motion with the given radius r :

$$U_2 = f(F_1, r) \quad (17)$$

If the radius is equal to $0.5l$ or 0 then

rotation on a track middle point axes or on the mass centre axes can be attained, respectively. However, a differential system has a transition period between setting the parameters and attaining them actually therefore a better solution would be use of already known force values for certain motion types, like the above mentioned rotation on the mass centre axes and rotation on a track middle point axes which can be easily accomplished by blocking one of the tracks (see 3.6).

If there is a necessity to attain a different radius than 0 or $0.5l$, then the system (17) is to be used.

4. METHODS USED

4.1 Parameter considerations

First it should be clarified which of the tracks should be referred as F_1 and F_2 . Obviously, it has to be related to the particular motion type that the robot has to carry out. For the simplest motion cases (discussed above) it would make no difference. For cases, when the system (17) is to be used, the most rational way to put the relation would be to designate the track force of greatest magnitude as F_1 . This is done with the reasoning that force with the greatest magnitude (corresponds to the outer rotation circle) theoretically may assume the greatest possible value, out of which, according to the system (17), the smaller value of F_2 (in this case) could be derived.

Turning to practical considerations about the value of F_1 , two restrictions have to be mentioned:

- theoretically, the value mustn't exceed the value of track static friction force R_{st} as mentioned in 3.7,
- the actual maximum value of F_1 is limited by the maximum motor driving voltage U_{1max} , which means that a constant value of F_1 can be maintained only for a certain period as the viscous resistance forces increase proportionally to the velocity.

Thus an optimum velocity control

algorithm should consider both restrictions. Practically it would mean switching on the control mode which provides the maximum acceleration under the given values of U_{1max} and R_{st} . In any case a maximum velocity depending on U_{1max} could be reached, beyond which no acceleration would be possible.

4.2 Computer programs

As a means for experimental analysis MATLAB Simulink software is used. It provides an opportunity to make block schemes based on differential equations including feedback loops, which allows to create schemes for exploring feedback-based control principles.

5. STATUS

Currently a computer study of basic control principles has been done, which involves two types of voltage U_1 inputs for F_1 , i.e., two types of control. The study is done without incorporating the force of the final equation (8) but, assuming that rectilinear motion is considered where both track forces are equal, this can be replaced by a reduced damping coefficient, which would involve the water resistance forces of the whole robot [3]. The input types are:

- Constant voltage input

This means that after a transition phase a constant velocity is reached (see Fig. 4), which is proportional to the value of input voltage. For practical purposes the maximum value of motor driving voltage should be used in this study.

- Maximum acceleration feedback voltage input

This means that a feedback loop [4] is made between the maximum acceleration value which can be derived from the value of R_{st} and the input voltage which increases as the velocity of robot increases. As mentioned in 4.1, the actual increase of velocity ceases as the maximum voltage value is reached. Thus at this moment system actually switches to the constant voltage input (see Fig. 5).

6. RESULTS

First, it could be concluded that with relevant medium parameter data and appropriately chosen component parameters adequate motion types and motion parameters could be provided.

Computer simulation results (see Fig. 4 and Fig. 5) regarding the rectilinear motion control are to be considered as of general importance, as the motor parameters were chosen arbitrary. The conclusion is that with the same parameters the transition period for constant (maximum) voltage input is slightly shorter (which is a rather expectable outcome) therefore an optimum control principle could be using the maximum input voltage until the maximum acceleration is reached (if it can be reached) and then switching to the maximum acceleration feedback voltage input. An alternative could be determining the maximum voltage value, by which the maximum theoretical acceleration motor would not exceed the maximum possible robot acceleration, beforehand and using this value as the constant input value.

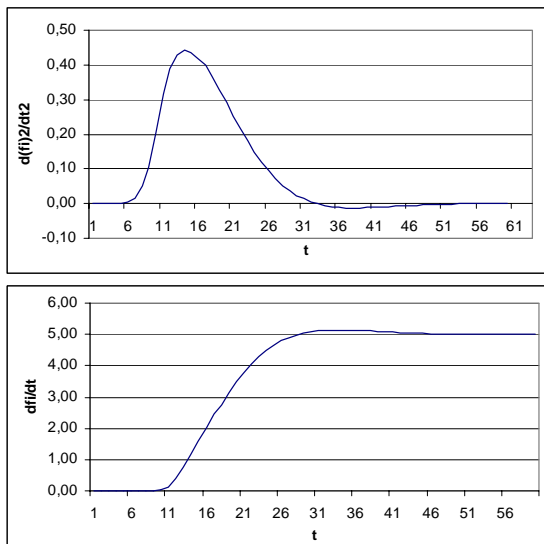


Fig. 4. Angular acceleration and velocity plots for constant voltage input

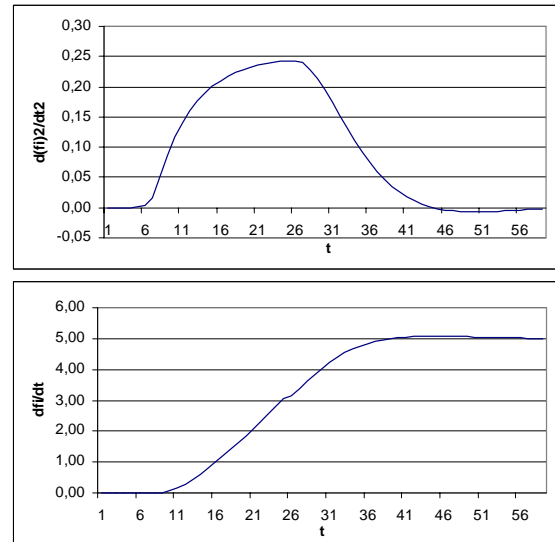


Fig. 5. Angular acceleration and velocity plots for variable voltage input

7. FURTHER RESEARCH

Further research could include, first, simulation of swerving motion according to (16) and, second, determination (experimental or mathematical) of the above mentioned maximum voltage value (see 6) and consequently simulation of both proposed control alternatives.

8. REFERENCES

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