Research Article

Analysis of Control Structure for Turning Maneuvers

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Although there have been a variety of studies about vehicular maneuvers on land or sea, maneuvers within a small area that require direction changes have rarely been discussed. The arrival or departure of ships to or from ports requires safe and effective turning maneuvers within a narrow area. In this study, we decompose the maneuver procedure into several operations, then establish an operational model, simplifying the behaviors of rudders and thrusters that operate the turning maneuver, ignoring the environmental factors. This proposed model is a unified model that can be applied to all types of ships, regardless of individual characteristics. Each operation is defined as an isolated procedure that has its own effect on the maneuver behavior and the whole maneuver procedure can be treated as a combination of these operations. A case study using this model to construct the optimal turning maneuver within a limited sea area is also provided.

1. Introduction

Unlike land-based transportation, there are various environmental factors and vessel characteristics that should be considered in the maneuver of ships offshore. It is difficult to establish a unified numerical model for ship maneuvers because the affecting factors described above are normally nonlinear [1, 2].

There are various designs for ships depending on their uses, meaning differences in length, weight, properties, and power of rudders and thrusters, all of which would affect the characteristics of the maneuvers a lot. Given these conditions, even if a numerical model is established, it would be difficult to apply to all kinds of ships. Some previous studies have discussed issues about ship positioning [3, 4], but it was necessary to define the basic conditions of an objective ship type. Most models could not be applied to all types of ships.
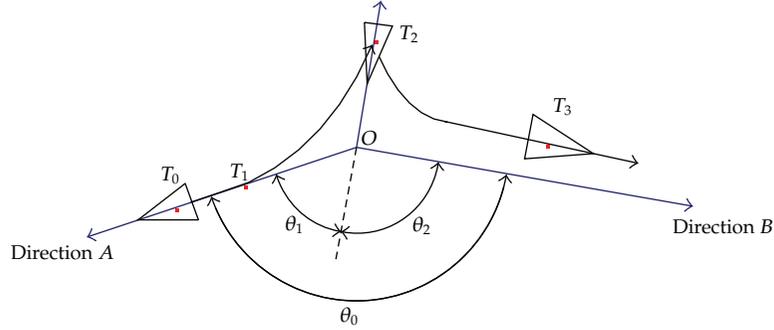
Figure 1: Ship turning maneuver.

In our study, we first observe the maneuver behavior of the Japanese training ship "Fukaemaru", a vessel belonging to the Faculty of Maritime Science, Kobe University, analyzing its behaviors during departure or approach within a limited sea area. Considering the existence of obstacles within such limited space, the turning maneuver normally has to be separated into two stages, moving forward and backward. There are certain conditions related to the available operational distances surrounding the ship that have to be considered in each stage.

The specific ship characteristics are not discussed here. The maneuver behavior is decomposed into several fundamental operations. The objective of the turning maneuver is achieved by their combination. We also discuss possible situations for the available maneuver operations surrounding the vessel. The objective is to establish a unified operational model as a foundation for research, which is not affected by individual ship characteristics. The actual implementation of this model could be established after experimental data is obtained for each operation for different types of ships.

2. Basic Control Method

By observing the behaviors of the "Fukaemaru" which has one propeller and bow and stern thrusters, we can find out some common maneuver characteristics. While turning, the forward maneuver is controlled by the rudder and the backward maneuver is mostly controlled by the thrusters.

The ship in Figure 1 moves backward dead slow. In the initial position T_0, it is facing direction A, but needs to turn to direction B on an azimuth θ_0 located near point O. In order to change the direction within a limited area, one feasible method is to stop the ship at point T_2, then only use the thrusters to operate the turning maneuver. On the other hand, if there is a wide sea area available, another maneuver, using the rudder to move ahead, could be carried out. There is also a general maneuver method in which backward thruster control and forward rudder control are used. We place appropriate upper limits on sailing speed and turning speed and specific turning angles needed to achieve the change in direction within the shortest period of time by passing the middle position T_2.

The ship should move backward at a fixed speed from its initial position T_0 and start to rotate at position T_1. In order to achieve the turning angle θ_0 at the objective position T_3 with direction OB, the ship should turn at position T_2 with an appropriate azimuth θ_1 and move forward with a reverse turning direction. If we define F_1 and F_2 as astern and ahead
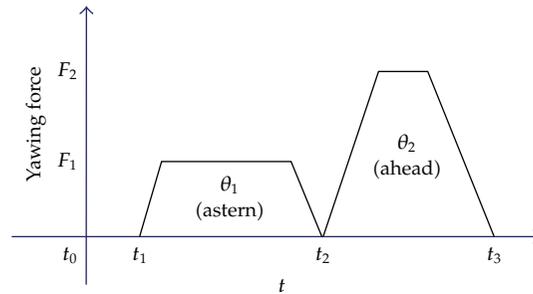
Figure 2: Control principle for turning maneuvers.

propulsive force, respectively, then the general control principle for turning maneuvers can be illustrated as in Figure 2. The backward maneuver is controlled only by thrusters and the forward maneuver is controlled only by the rudder.

Normally the forward maneuver is much easier to do than the backward for turning because of the difference in the location of pivoting point. Take "Fukaemaru" as an example. The positions of pivoting points are one-third ship length away from its bow and stern, respectively. Thus the turning moment of the forward maneuver is much bigger than that of the backward maneuver because the arm of torque is longer. The backward turning motion is mostly depending on the thrusters rather than the rudder; the rudder does not work during a low-speed backward maneuver. Compared with the rudder, the turning power of the thrusters is relatively small. Because of the above reasons, if we want to achieve the shortest time objective for the optimal turning maneuver, we should utilize the forward turning motion as much as possible, leaving the remaining part to be taken care of by the backward turning motion.

3. Operational Model

The control method is shown in Figure 2. Detailed forces and environmental factors are ignored in order to simplify the control motion equation used to analyze the basic control characteristics in comparison with the actual maneuver.

The objective of our study is to establish an effective maneuver procedure model for a large angle turning maneuver within a limited sea area. We also discuss the shortest operational time issue.

Unlike the turning maneuvers made by automobiles on land, there is some time lag between the actual initial activation of the rudders and thrusters and the start of the turning motion. This means that a relatively large turning diameter (typically at least two times the length of the ship for both forward and backward maneuvers) is needed. The turning maneuver is not such a serious issue when the ship is sailing on the open sea without any obstacles nearby, but it is important when the surrounding terrain factors have to be considered. This kind of situation often happens in limited areas such as when departing from or arriving at the port.

In order to discuss the behaviors within a limited sea area, we first define $D_{f\text{-min}}$ and $D_{b\text{-min}}$ as the minimum necessary turning diameters for a single forward and backward turn, respectively.
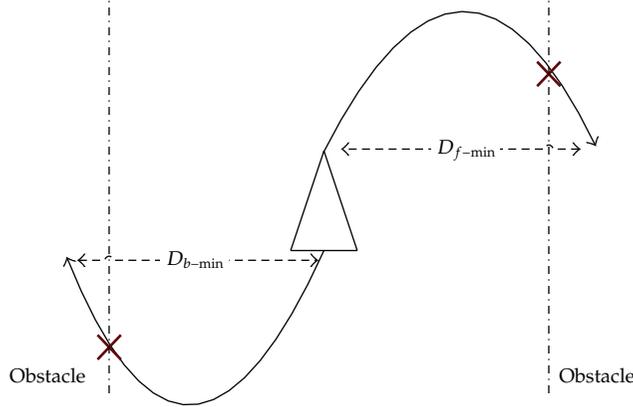
Figure 3: Minimum turning diameters.

Figure 3 illustrates the minimum turning diameters at forward and backward directions. The red cross symbols show that there could be conflicts if there are no enough space for turning maneuver operation. If obstacles exist and the distances of side clearance are less than the minimum single turning diameters, then the turning maneuver has to be separated into at least two stages.

Here, we focus on a considerable angle turning maneuver. The desired turning angle θ_0 might be defined as between 90 and 270 degrees. It is assumed that obstacles exist so other options except direct forward or backward turns have to be considered.

In order to establish a unified operational model, we separate the turning maneuver into several fundamental operations and describe their behavior. The proposed operations are listed below.

   (i) Forward turning [F]: move forward with a fixed speed and a turning motion.

   (ii) Backward turning [B]: move backward with a fixed speed and a turning motion.

   (iii) Rotation turning [R]: rotate at an almost fixed location.

   (iv) Halting operation [H]: slow down the speed almost to zero but still keep the turning motion.

   (v) Accelerating operation [A]: speed up from the stopping state and also keep the turning motion.

In order to simplify the description, we use symbols [F], [B], [R], [H], and [A] to represent the operations below. We also use O_i to represent each operation where i denotes the order of appearance starting from 1.

Now we can use the operation definitions to express the normal maneuver behaviors. Control sequence (C.S.) (3.1) defines the sequence of the fundamental control operations:

$$\text{C.S.} = [O_1][O_2]\cdots[O_n]. \tag{3.1}$$

An example of a generic backward departure from the pier appears in the format below: C.S. = [B], [H], [R], [A], [F]. In this example, O_1, O_2, O_3, O_4, and O_5 denote [B], [H], [R], [A], and [F], respectively.

Every operation would generate a corresponding turning angle after being adopted. We define the resultant turning angle caused by operation O_i as $\theta(O_i)$.

If the ship has to switch back, the maneuver can be divided into two stages, and a specific operation O_m is used to denote the relay operation between them. In formula (3.1), [H] is the relay operation O_2 and $m = 2$. The first stage is composed of O_1 to O_m, the second stage is composed of operation O_{m+1} to O_n.

Along with the sailing trajectory of each operation, we have to make sure that there is space enough to avoid obstacles. We define $X(O_i)$ as the occupied space, including an appropriate margin for each operation, S as the available sea area.

After all definitions are given, we use the total desired turning angle θ_0 and occupied space for each operation as the boundary conditions to evaluate the turning maneuver behaviors.

(i) For the turning angle restriction, (3.2) is given below:

$$\sum_{i=1}^{n} \theta(O_i) = \theta_0. \tag{3.2}$$

(ii) For the occupied space restriction, (3.3) is given below:

$$\bigcup_{i=1}^{n} X(O_i) \subset S. \tag{3.3}$$

After the boundary conditions with multiobstacles exist are given, we can search the control sequences for the shortest turning time from the operation sets that satisfy the restrictions.

4. Case Study

The options for turning within some areas with geographical restrictions are limited. Selection of the most effective maneuver operations is important.

We would like to look at a switchback maneuver as the ship departs from the pier as an example.

The initial conditions are set up as follows.

(a) The ship is initially stopped with the pier in the right side.

(b) The ship faces north.

(c) There is only one single obstacle to the east obviously, but there could also be more within this area as uncertain conditions.

(d) The turning motion must be made counterclockwise.

In order to simplify the boundary conditions for explaining our operational model, we assume that there is an obvious obstacle only in horizontal direction but not vertical direction in our test case. The horizontal available sailing distances (distances of side clearance) should be the controlling factor.
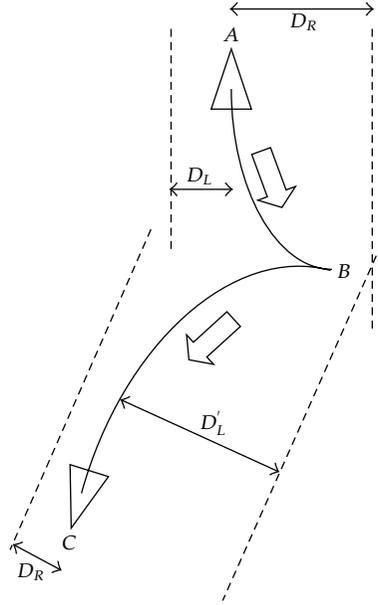
Figure 4: Backward turning maneuver.

If a ship needs to switchback in short time or there is no enough space for straight turning maneuver, the available maneuver operations could be illustrated as in Figure 4. The maneuver operations are separated into two stages as backward and forward stage. The backward stage denotes the ship moving process from point A to point B, and the forward stage denotes the ship moving process from point B to point C. The distances for side clearance restrictions are defined as D_L and D_R for the left and right sides according to the ship's initial position A. Subsequently, D'_L and D'_R are defined according to the ship's final position, C because its position and distances from surrounding obstacles have already changed.

Then we define $L(O_i)$ and $R(O_i)$ to represent the resultant horizontal moving distances affected by each operation for the left and right side, respectively, in the simplified occupied space conditions $X(O_i)$.

(i) The distances of side clearance restrictions, based on the ship's initial position and direction are calculated with (4.1) given below:

$$\sum_{i=1}^{m} L(O_i) < D_L,$$
$$\sum_{i=1}^{m} R(O_i) < D_R.$$

$$(4.1)$$

(ii) The distances of side clearance restrictions based on the ship's target course and direction, are calculated with (4.2) given below:

$$\sum_{i=m+1}^{n} L(O_i) < D'_L,$$
$$\sum_{i=m+1}^{n} R(O_i) < D'_R.$$

$$(4.2)$$

After all definitions are given, the possible courses and sequences of control operations can be listed to express the relationship between D_L, D_R, D'_L, D'_R, $D_{f\text{-min}}$, and $D_{b\text{-min}}$.

(i) Restriction (1): $D_L \geq D_{f\text{-min}}$
    Case (1):
    Operation: [A] [F]

(ii) Restriction (2): $D_R \geq D_{b\text{-min}}$
    Case (2.1):
    Operation: [B]
    Case (2.2):
    Operation: [B] [H] [A] [F]

(iii) Restriction (3): $0 < D_R < D_{b\text{-min}}$
    Case (3.1):
    Operation: [B] [F]
    Available distances:

$$L(O_1) < D_R,$$
$$L(O_1) + L(O_2) < D'_L, \tag{4.3}$$
$$R(O_1) + R(O_2) < D'_R.$$

Case (3.2):
Operation: [B] [H] [A] [F]
Available distances:

$$L(O_1) + L(O_2) < D_R,$$
$$L(O_3) + L(O_4) < D'_L, \tag{4.4}$$
$$R(O_3) + R(O_4) < D'_R.$$

Case (3.3):
Operation: [B] [H] [R] [A] [F]
Available distances:

$$L(O_1) + L(O_2) < D_R,$$
$$L(O_4) + L(O_5) < D'_L, \tag{4.5}$$
$$R(O_4) + R(O_5) < D'_R.$$

Case (3.4):
Operation: [R] [A] [F]
Available distances:

$$L(O_1) < D_R,$$
$$L(O_2) + L(O_3) < D'_L, \tag{4.6}$$
$$R(O_2) + R(O_3) < D'_R.$$
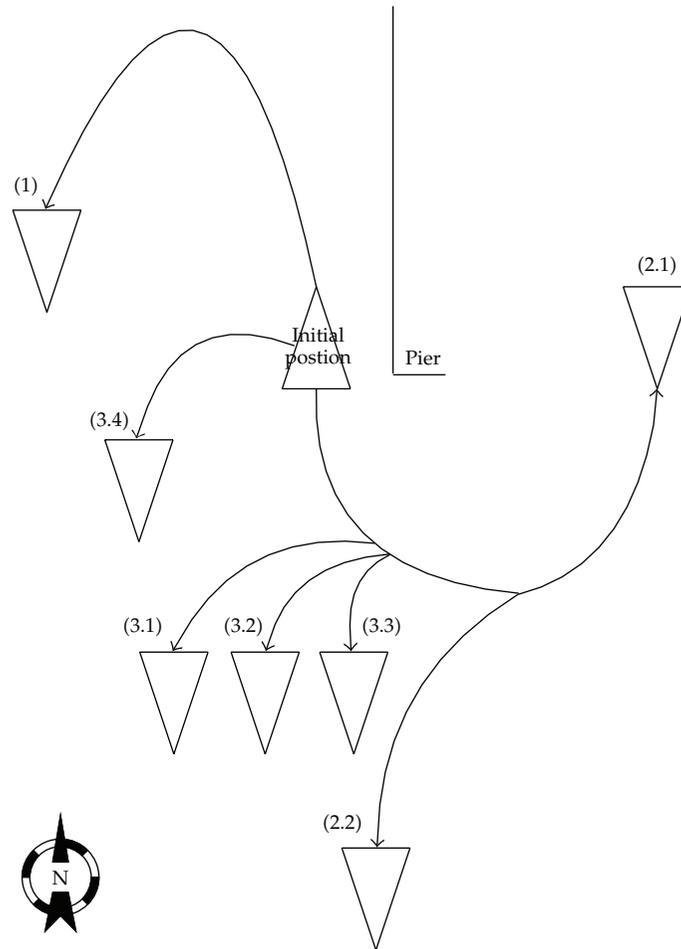
Figure 5: Possible maneuver cases.

We summarize the above cases and illustrate the possible courses in Figure 5. The obstacles in Figure 5 coule be plural. The pier is definitely one of the obstacles, but there could be more obstacles everywhere which would restrict available distances at particular direction. Obstacles are assumed to be standing still and in scattered places for representing geography conditions. The cases represent the feasible maneuver pattems under possible restricted situations. Cases (1) and (2.1) are available when no effect obstacles. The others cases are the results where the existence of obstacles is considered.

The focus of this paper is maneuvering within a limited sea area, so we would like to apply our operational model for the situations under restriction (3).

Case (3.1) is the simplest case and also the most common maneuver. It is very easy to apply because there are only two operations to take, but it may not be the most efficient course. With our model, the result is easy to get because if either one of these two operations is decided, the other one can be calculated automatically. Basically, cases (3.2), (3.3), and (3.4) are subdivisions of case (3.1).
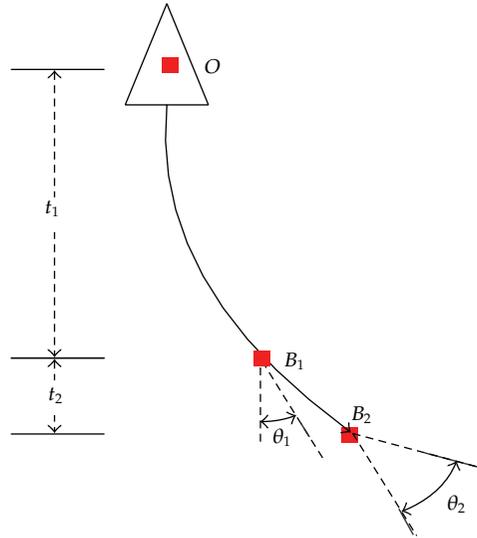
Figure 6: Diagram of backward maneuver.

In cases (3.2), (3.3) and (3.4), although there are multiple operations, but compared with [B], [F], and [R], operations [H] and [A] have relatively smaller effectsto turning angle change. So we can focus on the proportions between [B] and [F] in case (3.2), [B] and [R] in case (3.3), and [R] and [F] in case (3.4) to generate the approximate solutions. Each operation has different motion characteristics and their work time should be decided based on the available geographical conditions.

Figures 6 and 7 show details of the forward and backward maneuvers, respectively. We would like to use these to explain the optimal control for case (3.2).

In Figure 6, a ship moves backward from point O to point B_1 with time t_1; the change in angle is θ_1. Then, the [H] is executed to slow down and move to point B_2 by time t_2; the change in angle is θ_2.

In Figure 7, a ship executes [A] to accelerate and change its position from point O' to point F_1 with time t_3; the change in angle is θ_3. Then, [F] is executed to move forward to point F_2 by time t_4; the change in angle is θ_4.

We assume that the turning angle θ_4 is the variable that needs to be calculated here. Normally, we can treat t_2 and t_3 as almost fixed values, because the operation time is relatively short. So the shortest maneuver time is to minimize $t_1 + t_4$ based on formula (3.2), $\theta_1 + \theta_4 = \theta_0 - \theta_2 - \theta_3$. If we already know the operational characteristics of [F] and [B] in advance, then we can calculate θ_4 by giving an appropriate t_1 to decide θ_1. Finally, we can calculate t_4 given the characteristics of [B]. Also, in the opposing case, we can first give an appropriate t_4 to decide t_1.

Normally, we can say that the yawing ability of [F] is larger than [B], so the more effective maneuver is to use [F] as much as possible. The maximum t_4 can be obtained by using the maximum horizontal distance within D_R; then [B] can be used to achieve the remaining necessary turning angle. By calculating t_1 for [B], the position of point B_2 can be decided. If the position of B_2 is within the available sea area, then the procedures for case (3.2) are applicable. This procedure is the shortest time maneuver.
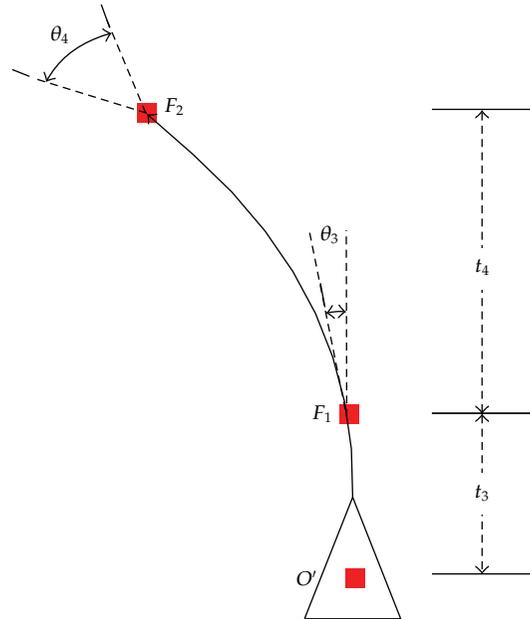
Figure 7: Diagram of forward maneuver.

On the other hand, if the position of point B_2 is not allowed, case (3.3) or case (3.4) has to be considered. With those cases, [B] or [F] is replaced by [R]. We assume that the effect of horizontal motion by [R] is small enough that it can be ignored, and we spend time interval t_5 to get a rotating angle θ_5. Normally, compared with [F] and [B], operation [R] would require more time, because the movement is less, so use the maximum [F] or [B] and the remainder by [R] for the shortest time maneuver.

The course decision-making flowchart summarizing the above maneuver procedures is illustrated in Figure 8.

In this section, we discuss only one example, the counterclockwise backward departing maneuver case. The clockwise or arriving maneuvers could also be easily applied, so the details are not given here.

The operational model is to build a foundation for an automatic maneuver selection procedure. We would like to define a ship turning maneuver model that is not related to vessel type. This is done by subdividing the maneuver operation and defining the available sea area.

Since the objective of our model is to design a unified operational model, the details of the ship maneuver are not given in this paper. For the actual applications, our model should be applied after experiments for each operation are executed.

5. Conclusion

A basic operational model for ship turning maneuvers within a limited sea area is described in this paper. We also use a test case to explain how to generate the approximate optimal solution, simply ignoring some relatively small effects but focusing on the effectiveness of the operations. This model can be used not only for the automation of turning maneuvers and to facilitate tugboat control, but also to come up with a standard for evaluating turning maneuvers.
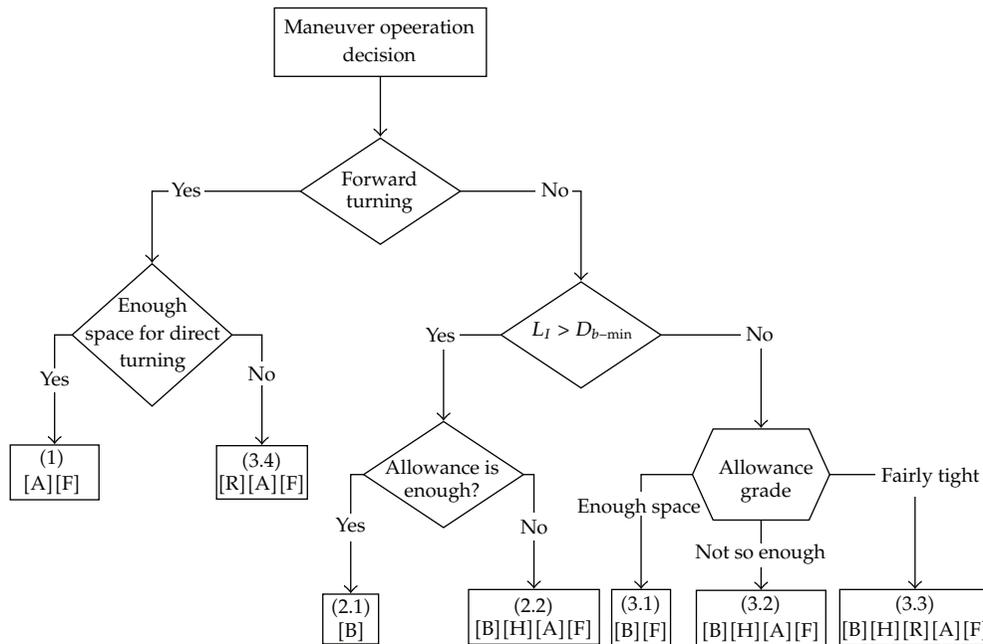
Figure 8: Maneuver operation decision-making flowchart.

Our future research objectives will focus on issues of automatic and dynamic control for vessels departing from or arriving at piers. Also, environmental factors such as wide and tide, which we ignore in this paper, but important in actual maneuver operations will be incorporated. The establishment of a numerical simulation method is another possible research direction.

Acknowledgments

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