Real Time Path Planning for a Class of Torpedo-Type AUVs in Unknown Environment

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Abstract-**This paper presents a path planning scheme for a class of torpedo-type AUVs in unknown environments. Consider the case where an underactuated vehicle (similar to a carlike robot) is travelling in completely unknown environments. In this case, due to deficiency of necessary information, quite number of graph generation and corresponding graph searching methods cannot be directly applicable. In this paper, a VRBVG (virtual rubber band visibility graph) method is proposed to generate a visibility graph under the assumption that $C_{unknown}$ (outside of the vehicle's sonar coverage) does not include any obstacle. Using this graph, a simple A* search algorithm with the travelling time taken as the heuristic cost function is applied to find a path. Since the environment is unknown, the proposed planning method can only provide kind of suboptimal path.**

Keywords-path planning; visibility graph; torpedo-type AUV; heuristic cost function; A* algorithm

I. INTRODUCTION

Fueled by rapidly maturing industry, quite a number of technologies such as advanced sensing and data processing are available for us to develop various AUV underwater behaviors. Nonetheless, by now most of these missions are still carried out through user interfaces. How to improve the vehicle's autonomy has become one of most important challenges in today's ocean exploration. It has been clear for decades that autonomous path planning including obstacle avoidance is one crucial requirement for AUV technologies.

Path planning has been an intense research topic for UGV and UAV in the past decades. Due to its intuitiveness and simplicity, potential field method has been widely used for robot's collision avoidance, though how to effectively escape from its local minima is still remain open [5],[7]. On the other hand, various matured graph search algorithms also have been easily adjusted and applied to robot technology [12],[7]. These methods include breadth-first, depth first, bright first (Dijkstra algorithm) and A* algorithm with different heuristic cost functions, and corresponding graph generation methods have visibility graph [15], Voronoi diagram [4] or quad tree. All of these methods need to know the environment *in priori*. The recent search algorithms, such as D* algorithm [17], focused D* algorithm [18], LPA* algorithm [6] can provide advanced calculation performance and robustness to the unknown or partially-known environment. However, to maximize its planning performance, these methods still need to acquire at least the partial knowledge of the environment.

In this paper, we consider the case where the torpedo-type underactuated vehicle is travelling in an unknown underwater environment with nonzero sea current/flow. There is a 2D forward looking image sonar mounted in front of the vehicle for the purpose of obstacle detection. Outside of the sonar coverage area is assumed to be totally unknown. Nonetheless, in this paper we assume that there is not any obstacle in this unknown area. Under this inevitable assumption, we can get a kind of visibility graph called *RBVG (rubber band visibility graph)*. Since this graph is different from the real one, we call it *virtual RBVG*. Using this graph, we search the path by applying A* algorithm with the travelling time taken as the heuristic cost function. In the calculation of travelling time, the sea current influence is also considered. Some simulation studies are carried out to illustrate the effectiveness of the proposed path planning scheme.

II. TORPEDO-TYPE AUVS

A. Vehicle Dynamics

For torpedo-type AUV, its horizontal kinematics and dynamics can be expressed as following [1],[10]

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\psi}\end{bmatrix}=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}u\\ v\\ r\end{bmatrix}$$

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}f_u(u,v,r)\\ f_v(u,v,r)\\ f_r(u,v,r)\end{bmatrix}+\begin{bmatrix}b_u & 0\\ 0 & 0\\ 0 & b_r\end{bmatrix}\begin{bmatrix}\tau_u\\ \tau_r\end{bmatrix}+\begin{bmatrix}d_u\\ d_v\\ d_r\end{bmatrix}, \qquad (1)$$

where (x, y) denotes vehicle's position, ψ is yaw angle; u, v, and r are the velocities in the body-fixed frame, each in the surge, sway, and yaw direction; f_u, f_v, f_r denote the vehicle's nonlinear dynamics; surge force τ_u and yaw moment τ_r are control inputs with nonzero constant gains b_u and b_r; and d_u, d_v, d_r denote disturbance terms such as ocean currents.

Usually, the only available two control inputs τ_u and τ_r are not completely independent. In fact, given a torpedo-type vehicle, we have $\tau_r \propto u^2\delta_r$ with δ_r rudder angle. Therefore, to active its yaw dynamics, the vehicle should keep nonzero forward speed, in other word, $u(t) \geq u_{\min} > 0$. On the other hand, due to the hydrodynamic damping, the vehicle's forward speed u can only take limited value. And limited yaw moment τ_r further causes the vehicle's turn rate r also to be $r \le r_{\max}$. Consequently, we have

$$R(t) \ge R_{\min} = u_{\min} / r_{\max}, \quad t \ge 0, \tag{2}$$

where R is vehicle's turn radius.

B. Underwater Localization

Because of difference between the transmission mediums, quite number of matured technologies such as GPS and other radio localization methods do not work underwater. For this reason, underwater localization or positioning has become the most crucial issue in the underwater technology community. Today, several underwater positioning technologies such as long baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL) systems are available for robots' underwater voyages [11]. However, for all of these acoustic systems, surface vessels are needed to support the positioning operation.

From operating cost point of view, inertial navigation system (INS), especially strapdown INS (SDINS), might be a satisfactory alternative option for underwater positioning. Inertial navigation is the process of integrating acceleration and angular rate measured by inertial measurement unit (IMU) over time to calculate the velocity and attitude, and further to estimate position. Therefore, the unknown bias terms in the IMU measurements can cause the navigation results to be drift over time. To compensate these drifts, the bias terms are usually estimated through proper estimation methods such as Kalman filter, particle filter, and so on. And today's sensing technology can provide a good number of reference sensors to construct the above mentioned estimation schemes, for more details, refer to [9] and references therein.

Recently, the simultaneous localization and mapping (SLAM) method has become an interesting candidate for underwater localization [6],[13]. In this case, how to properly extract the feature (vector) is the most crucial issue. In the remainder of this paper, we will not further consider the vehicle's detailed localization method, just assume there is proper one and its positioning error is simply considered in the quantification of the parameter d_C which is defined later in the Section III.

C. 2D Forward-Looking Image Sonar

In this paper, a kind of 2D forward looking image sonar is considered for obstacle detection. The sonar view angle is 90°x20° and maximum range is 100m. Moreover, the sonar image update rate is up to 15Hz, therefore, is suitable for underwater vehicle to detect the obstacle on-line.

The procedure of obstacle detection and its modeling is shown in Fig. 1. In the case where the vehicle is wandering in an unknown environment, at any t>0, the total environment can be divided into two parts: *known area* and *unknown area*. Here *known area* means the sonar recovery area at t>0, and the rest of the environment is naturally called as *unknown area*. In the case of 2D sonar, at t>0, two obstacles B_1 and B_2 are perceived as each of dot areas B_1' and B_2', which are further modeled as polygons of $A_1A_2A_3$ and $C_1C_2C_3C_4C_5$. For more details about obstacle modeling, the readers can refer to the Section III. In practice, other kinds of modeling methods also can be applied according to the different practical conditions.

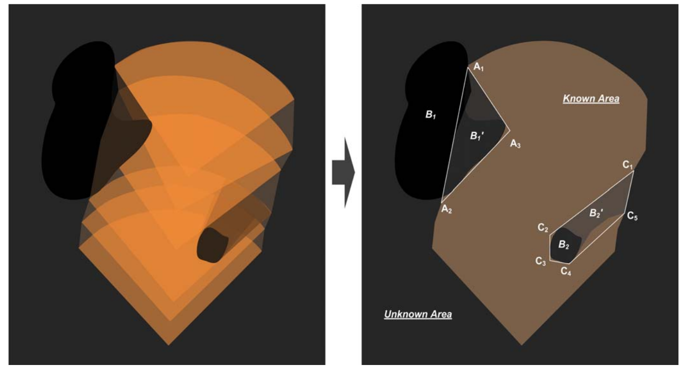


Fig. 1 This figure shows the procedure of obstacle detection and modeling using 2D FL sonar. At t>0, two obstacles B_1 and B_2 are modeled as polygons $A_1A_2A_3$ and $C_1C_2C_3C_4C_5$.

III. Real Time Path Planning

As aforementioned, the main operating field of P-SURO AUV is in a cuboid basin. In this paper, part of its navigation environment (basin wall information) is available. Under this assumption, we propose a simple SLAM method using range sonar. This method consists of two steps, obstacle detecting phase and navigation phase. In the obstacle detecting phase, through rotating motion, the vehicle can detect the obstacle and further can get map of the environment. According to this map, the vehicle plans desired path and takes corresponding path tracking.

A. Configuration Space and C-obstacle

On the horizontal plane, a configuration q is a specification of the position (x, y) and heading ψ of the vehicle. The configuration space C is the space of all configurations. In this paper, the vehicle is considered as a point with maximum curvature $\kappa_{\max}$. Moreover, the obstacles are modeled to take polygon shapes.

Definition 1. Given obstacle B or obstacles B_i with $B = \cup_i B_i$, let $\beta = \partial B$ and $C_{O-free} = C \setminus B$. For $q \in C_{O-free}$, we define

$$clearance(q) = \min_{p \in \beta} \| q - p \|. \tag{3}$$

Free space is the set of

$$C_{free} = \{q \in C / clearance(q) \ge d_C\}, \tag{4}$$

where d_C is a design parameter. And correspondingly, $C-obstacle$ is defined as

$$CB = C \setminus C_{free}. \tag{5}$$

Remark 1. From safety point of view, in (4), the parameter d_C should be carefully chosen according to the vehicle's navigation accuracy, exterior disturbances such as ocean current, and so on. And more importantly, it satisfies $d_C > 2R_{\min}$ where $R_{\min}$ is defined in II-D.

The *known area* maps in C to the region of C_{known}, and the *unknown area* maps to $C_{unknown}$.

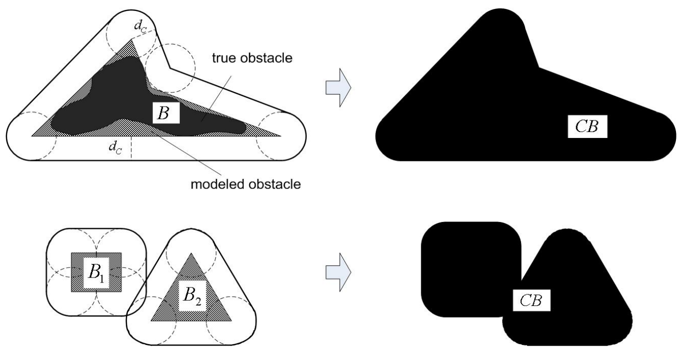


Fig. 2 This figure shows examples of *C-obstacle*. *CB* is obtained by growing *B* isotropically by the radius of d_c [5]. In some cases, separated obstacles can be mapped in *C* to the same connected region.

B. RB Visibility Graph

Unlike to the *generalized visibility graph* defined in [5], in this paper, we introduce a kind of modified visibility graph. Assume there is a rubber band satisfying the following conditions:

C1. It ends up at q_{init} and q_{goal}, and the length satisfies $l_{RB} \le \| q_{goal} - q_{init} \|$.

C2. It cannot pass through *CB*.

C3. It will never intersect itself.

A configuration *s* of rubber band is the band shape, which represents one of the path from q_{init} to q_{goal}. Let *S* denote the set of all possible *s* satisfying *C1* ~ *C3* in the vehicle's configuration space. For all of $s_i \in S,\ i = 1, \cdots$, *RB visibility graph*, denoted by *G*, can be defined as follows:

1. q_{init}, q_{goal} and all points where rubber band separates from *CB* are nodes of *G*.

2. Let a and a' be of two nodes defined in 1. If the open segment joining a and a' lies entirely in free space and is a tangent segment to *CB*, then it is a link of *G*.

3. Among all edges of *CB* connecting two adjoined nodes, only the ones contacting with rubber band are links of *G*.

4. If line $q_{init}q_{goal}$ does not intersect with *CB*, then $q_{init}q_{goal}$ is a link of *G*.

As aforementioned, in this paper, we consider the case where the vehicle wanders around in unknown environment. In this case, it is difficult or impossible to get a complete RB visibility graph. For this reason, in this paper we make the following assumption.

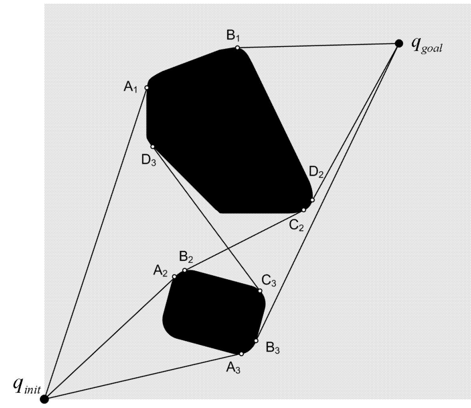


Fig. 3 This figure shows a simple RB visibility graph in C-space with two obstacles. In this case, set *S* contains total of 5 rubber band configurations: $q_{init}A_1B_1q_{goal}$, $q_{init}A_2B_2C_2D_2q_{goal}$, $q_{init}A_3B_3q_{goal}$, $q_{init}A_1B_1D_2C_2B_2A_2A_3B_3q_{goal}$, $q_{init}A_3B_3C_3D_3A_1B_1q_{goal}$. The points marked as small circles are the nodes of *G*. Among all edges of *CB* connecting each of two adjoined nodes, C_2D_3 and B_2C_3 are not links of *G*.

As aforementioned, in this paper, we consider the case where the vehicle wanders around in unknown environment. In this case, it is difficult or impossible to get a complete RB visibility graph. For this reason, in this paper we make the following assumption.

Assumption 1. $C_{unknown} \cap B = \varnothing$. In other word, there is not any obstacle in the *unknown area*.

Remark 2. Due to the fact that the vehicle is wandering in an unknown environment, only a kind of suboptimal path is available, if there were one. Under this consideration, in this paper, the current vehicle configuration *q(t)* is treated as q_{init} in the getting of visibility graph at t>0.

With *Assumption 1*, $\forall\ t > 0$, we can get the correspondent RB visibility graph. Since this graph is different from the exact one, we call it *virtual RB visibility graph*.

C. Heuristic Cost Function

In most of literature on path planning, distance (Cartesian distance from current configuration *q(t)* to q_{goal} or distance to q_{goal} passing around the obstacles [7]) is usually taken as the heuristic path cost function. However, in some cases where robot wanders in the environment with exterior disturbances such as wind or ocean current, the shortest distance usually does not represent the shortest path. In the case of underwater vehicles, especially for AUVs, energy problem is one of most crucial issues. Therefore, the shortest path is usually taken as the one with the shortest travelling time instead of distance. Taking travelling time as heuristic cost function for graph search is the similar case as in [4].

At t>0, the vehicle's velocity can be expressed as $\vec{u}(t) = \vec{u}_r(t) + \vec{v}_c(t)$, where $\vec{u}_r$ is the vehicle's relative speed to the current and $\vec{v}_c$ denotes the current speed.

Assumption 2. $\forall t > 0,\ |\vec{u}_r(t)| = c_u,\ |\vec{v}_c(t)| = c_v$ where c_u, $c_v > 0$ are constant. Moreover, the direction of ocean current is unvarying throughout the vehicle's underwater mission.

The travelling time of path s_i from current configuration to q_{goal} is given by

$$t_{si} = \frac{d_{si}}{|\vec{u}|} = \frac{d_{si}}{c_v \cos\alpha + \sqrt{(c_u^2 - c_v^2) + c_v^2 \cos^2\alpha}}, \quad (6)$$

where d_{si} is the length of path s_i, α is the angle between $\vec{u}$ and $\vec{v}_c$. For derivation of (6), see *Appendix 1*.

D. Path Planning

At each t>0, for given (virtual) RB visibility graph, A* algorithm [3] with travelling time of (6) being a heuristic cost function is applied as search engine to find an optimal path. In fact, since the vehicle is wandering in an unknown or partially known environment, this path only can be suboptimal.

Here, it is of interest to consider some possible peculiar cases during the graph searching.

1) Multiple Same Cost Paths. In this case, various standpoints can be considered. From obstacle avoidance point of view, the path which adjoins more obstacles will increase the risk of collision. It is also of common sense that the path with more pieces located in $C_{unknown}$ will increase the collision risk. If two paths have the same length of links adjoining obstacles and also the same length of pieces located in $C_{unknown}$, then we can simply pre-define the vehicle to always take the right sided path, or vice versa, see Fig. 4.

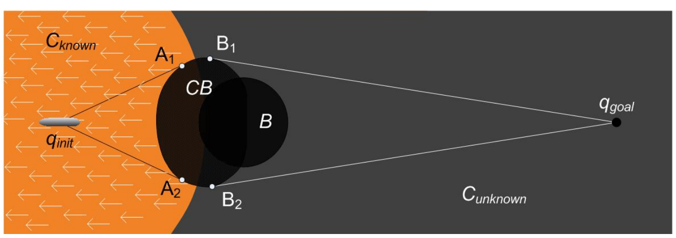


Fig. 4 This figure shows an example of two of same cost paths. Two paths $q_{init}A_1B_1q_{goal}$ and $q_{init}A_2B_2q_{goal}$ have the same lengths, and the sea current flows face to the vehicle. In this case, it is obvious that these two paths have the same heuristic cost expressed as (6).

2) Wall following. Consider the case as shown in Fig. 5. $\forall t_k > 0, k = 1, \cdots$, if the cost of the path $q_{init,tk}A_1B_1q_{goal}$ is larger than the one for $q_{init,tk}A_kB_kq_{goal}$, then the vehicle will follow the wall B along the right direction[1]. If the wall extends to the right infinitely, then the vehicle will also follow infinitely. This means that in some cases, the algorithm presented in this paper may not find the path even if there is one (in Fig. 5, it is easy to see that there is a finite length of path connecting to q_{goal} along the left side of the wall). It is notable that if the sea current flow from right to left or q_{goal} approach to B_1 more closely, then there will be $t_k > 0$ such that the cost of the path $q_{init,tk}A_1B_1q_{goal}$ is less than the one for $q_{init,tk}A_kB_kq_{goal}$, and therefore the vehicle can find the path approaching to q_{goal}.

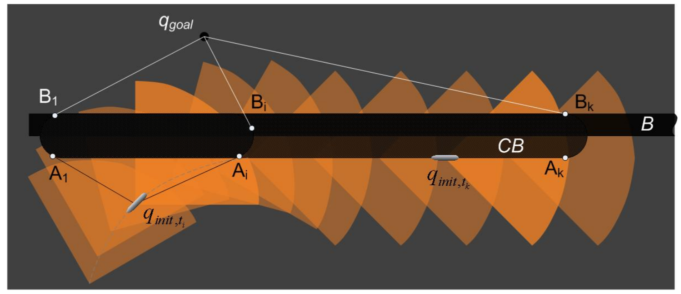


Fig. 5 This figure shows a case where the vehicle follows an infinite length of wall. The location of q_{goal} and the external conditions such as sea current might determine if the vehicle can or cannot find a path.

IV. Simulation Studies

In this section, we carry out some numerical simulations to illustrate the effectiveness of proposed path planning scheme. In the simulation, we directly apply the six degree of freedom nonlinear dynamics of REMUS AUV [14]. Throughout the simulation, the vehicle is assumed to take the constant forward speed u_d, and its reference heading value can be got from the proposed path planning scheme.

At any t>0, the path planning algorithm provides the reference heading of the path, which can be denoted as ψ_d. Without sea current, the vehicle's reference heading ψ_r can be simply taken as ψ_d. However, nonzero sea current/flow is unavoidable in practical applications. If the sea current takes constant velocity u_c with the direction of ψ_c, then ψ_r can be calculated as following

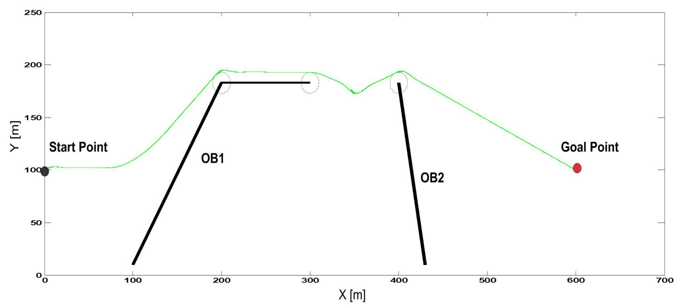
$$\psi_r = \begin{cases} \psi_d + \arccos\left(\dfrac{u_d^2 + u^2 - u_c^2}{2u_d u}\right), & if\ \ 0 \le \psi_d - \psi_c \le \pi \\ \psi_d - \arccos\left(\dfrac{u_d^2 + u^2 - u_c^2}{2u_d u}\right), & else \end{cases} \quad (7)$$

where $u = |\vec{u}|$ is defined in (6). Given (u_d, ψ_r), the vehicle control input (τ_u, τ_r) is calculated using a method similar to the one in [10].

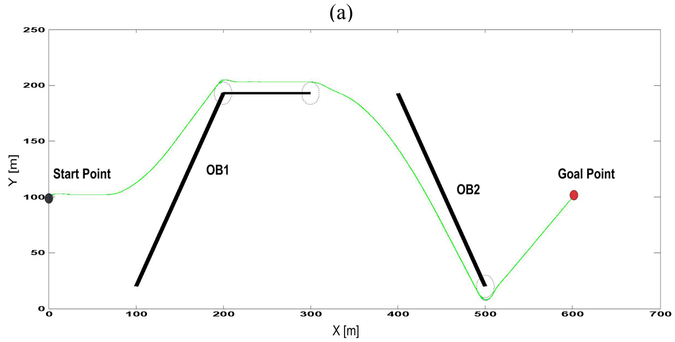
Simulation results are shown in Fig. 6 and Fig. 7. Fig. 6(a) and 6(b) are the same case except that the arrangement of OB2 is slightly modified. As aforementioned, the proposed path planning method is adjusted for the case where the vehicle is wandering in a totally unknown environment. In this case, it is impossible to find the optimal path online. Fig. 7 is captured by zooming in the Fig. 6. In Fig. 7, we can see the desired path ψ_d and corresponding vehicle heading ψ_r. In the simulation, we take u_c =1.0knots and ψ_c =π. Here, it is notable that the vehicle moving velocity u is dependent on ψ_d. Therefore, it is kind of complicated to calculate the travelling time while the vehicle tracking an arc trajectory. In the simulation, the travelling time is approximated using an average velocity of

[1] In fact, there is a slight shift in the position of node A_1, which is ignored for the convenience of discussion.

$(u_s+u_e)/2$ where u_s is the entrance velocity and u_e is the end velocity of arc motion.



(a)



(b)

Fig. 6 This figure shows the comparison of path planning results of two of the same cases except one of the obstacles is slightly changed its arrangement.

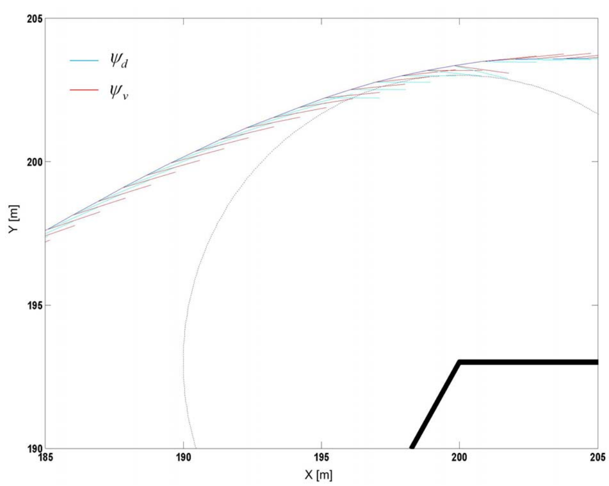


Fig. 7 This figure shows the path planning ψ_d and its corresponding vehicle heading ψ_r.

V. Conclusion

In this paper, we have proposed a path planning scheme including obstacle avoidance for a class of torpedo-type AUVs travelling in unknown environments with nonzero sea current or flow. There is a 2D forward looking image sonar mounted in front of the vehicle for the purpose of obstacle detection. Outside of the sonar coverage area is assumed to be totally unknown. Under an inevitable assumption that there is not any obstacle in this unknown area, we get a *virtual RBVG*. Using this graph, we search the path by applying A* algorithm where the travelling time is taken as the heuristic cost function. In the calculation of travelling time, the influence of sea current/flow is also considered. We've also carried out some of simulation studies to illustrate the effectiveness of proposed path planning scheme.

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Appendix 1. Derivation of Equation (6)

Consider the velocity triangle seen in Fig. A-1. According to the *law of cosine*, we have

$$c_u^2 = c_v^2 - 2c_v u\cos\alpha + u^2, \qquad \text{(A-1)}$$

where $u = |\vec{u}|$. Further, we can get

$$u = c_v\cos\alpha \pm \sqrt{(c_u^2 - c_v^2) + c_v^2\cos^2\alpha}\,. \qquad \text{(A-2)}$$

Since we only accept $u > 0$, (A-2) can be rewritten as

$$u = c_v\cos\alpha + \sqrt{(c_u^2 - c_v^2) + c_v^2\cos^2\alpha}\,. \qquad \text{(A-3)}$$

Using (A-3), it is straightforward to get (6).

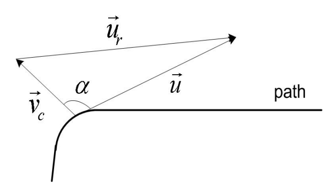

Fig. A-1 Vehicle velocity composition.

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