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Araştırma Makalesi / Research Article

# A Stable Path Following Algorithm Based on Adaptive Target Points for Unmanned Surface Vehicles

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**Abstract**

This study proposes a stable and robust path following algorithm for Unmanned Surface Vehicles (USVs). The main objective of this paper is to optimize a key parameter in the improved algorithm to minimize tracking errors. In this study, firstly a stability criterion is developed to limit this parameter and make stable navigation. This model determines the unique target points for each time step using the optimum and flexible parameter in contrast fixed value used in previous studies. The proposed stability criterion and the turning rate data obtained from the previous time step are used to determine this optimum parameter. It provides smooth and precise navigation at critical points like as sharp turning maneuvers. Moreover, it includes saturation for maximum turning rate to make realistic navigation. The proposed model in this study reduces tracking errors by around 20% compared to the conventional carrot-chasing algorithm. Finally, a numerical simulator for USVs in the Matlab environment has been included in the Appendix to support the work of other researchers.

**Keywords:** Unmanned Surface Vehicle, Path Following Algorithm, Tracking error.

# İnsansız Su Üstü Araçları için Uyarlanabilir Hedef Noktalarına Dayalı Kararlı bir Yol İzleme Algoritması

**Öz**

Bu çalışma, insansız su üstü araçları için kararlı bir yol izleme algoritması önermektedir. Bu makalenin temel amacı, izleme hatalarını en aza indirmek için geliştirilmiş algoritmadaki bir anahtar parametreyi optimize etmektir. Bu parametreyi sınırlandırmak ve istikrarlı bir seyir yapmak için kararlılık kriteri belirlenmiştir. Bu model, önceki çalışmalarda kullanılan sabit değere karşılık optimum ve esnek parametreyi kullanarak her zaman adımı için benzersiz hedef noktalarını belirler. Önerilen kararlılık kriteri ve önceki zaman adımından elde edilen dönüş hızı verileri bu optimum parametreyi belirlemek için kullanılmaktadır. Bu çalışmada geliştirilen yöntem, keskin dönüş manevraları gibi kritik noktalarda daha düzgün bir seyrin gerçekleşmesini sağlar. Ayrıca, gerçekçi seyir yapmak için maksimum dönüş hızı için bir üst sınır içerir. Bu çalışmada önerilen model, geleneksel yol izleme algoritmasına kıyasla izleme hatalarını yaklaşık %20 oranında azaltmaktadır. Son olarak, diğer araştırmacıların çalışmalarını kolaylaştırmak için Matlab ortamında hazırlanan sayısal bir simulator, çalışmanın sonuna eklenmiştir.

**Anahtar Kelimeler:** İnsansız Su Üstü Aracı, Yol Takip Algoritması, İzleme hatası.

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## 1. Introduction

Oceans account for more than 90% of the world's water and more than 80% of the oceans haven't been discovered yet. The oceans contain the greatest wealth of natural resources for human beings. The exploration, monitoring, operation, and protection of the oceans are critical to effectively using this natural resource treasure and mitigating the impact of global climate change (Zereik et al., 2018). Autonomous vessels can undertake a variety of maritime operations such as marine data collection and resource exploration, environmental sampling and monitoring, coastal surveillance, reconnaissance, and patrol (Peng et al., 2020; Shi et al., 2017; Liu et al., 2016; Shi et al., 2017; Campbell et al., 2012). Through the development and increased use of autonomous marine vehicles, it is possible to reduce personnel costs and increase operational efficiency.

Path following algorithms are increasingly being used in autonomous marine vehicles due to their adaptability and resilience. Many researchers (Gu et al., 2022), (Garcia & Zangwill, 1981), (Bibuli et al., 2007), (Keller, 1987), (Gould & Tolle, 1983), (Rheinboldt, 1986), (Allgower & Georg, 1993), (Todd, 1976a) and (Seydel, 1988) studied the improvements in numerical path following in terms of adaptations, efficiency, applications, and complexity analysis. Some of these studies in the field of path following were adapted to the maritime sector and autonomous marine vehicles were designed.

One of the methods used in the path following algorithm is the carrot chasing algorithm in the literature. It is preferred by many researchers (Perez et al., 2019; Chung et al., 2020; Jin et al., 2020) due to its simplicity and easy applicability. Moreover, it is an effective technique to catch the desired path for USVs. However, it has a weakness. In the carrot chasing algorithm, a fixed parameter is used to determine target points ignoring stability condition, maneuverability (maximum turning angle per second), and current position of the autonomous vehicle. This omission leads to substantial tracking errors; furthermore, it causes unstable navigation in some cases. This study proposes a robust flexible value for this crucial key parameter considering turning rate and position of the USV. This flexible parameter is limited to a stability condition improved in this study to make stable and accurate navigation. The proposed algorithm uses the unique target points derived from the flexible value for each time step. The developed algorithm for USVs decreases tracking errors by around 20% compared to the carrot-chasing algorithm.

## 2. Materials and Methods

The large percentage of USV tasks are based on linear lines following the model and this study deals with it. Cross-track error is the difference between the current position of the vehicle and the planned route. The first expectation from a proper path following algorithm is to minimize the cross-track error. Secondly, it must reduce the difference between the predefined course angle and the vehicle course angle.

There are two types of path following algorithms namely geometric algorithms (Conte et al., 2004; Naini, 2015; Sujit et al., 2014; Nelson et al., 2007; Meenakshisundaram et al., 2010) and control-based algorithms (Lee et al., 2010; Miao & Fang, 2012; Subbarao & Ahmed, 2014). Geometric algorithms are simple to implement and easy to understand. One of the most commonly used geometric algorithms is the Carrot Chasing algorithm. It generates a virtual target point on the desired path to determine the course angle in each time step. Just as a rabbit chases a carrot, the USV continuously follows this virtual target point. The course angle of USV is determined according to this virtual target point. Therefore, the virtual target point on the predefined path must be selected properly to make stable and accurate navigation. Schematic of two-dimensional Carrot Chasing Algorithm has been shown in Figure 1. In Figure 1, W(i) is previous or initial desired target point, W(i+1) is desired target point, the distance between W(i) and W(i+1) is desired path, USV represents the unmanned surface vehicle, the planned point on desired path is the virtual target point (VTP) of USV, d is the minimum distance between the desired path and the USV which means cross-track error, Ψ represents current course angle, Ψd represents desired course angle determined according to the virtual target point and δ is a key parameter to make the best navigation.

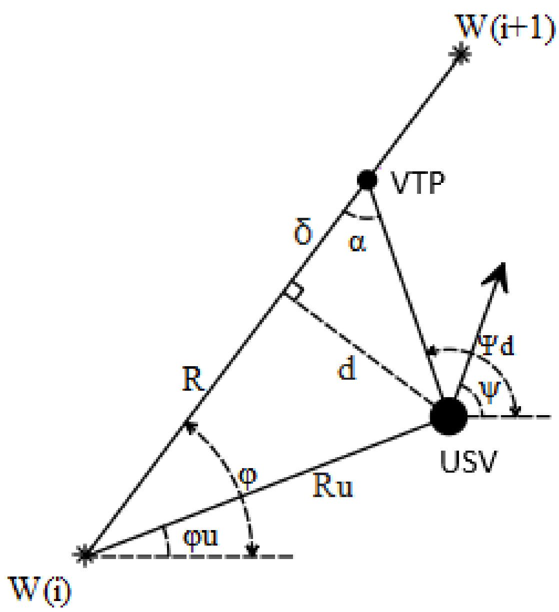


**Figure 1.** The Carrot Chasing Algorithm.

The conventional Carrot Chasing Algorithm uses a fixed δ for every time step. However, the unique δ value in each time step must be determined according to the position and turning rate of USV to make accurate and stable navigation. This paper proposes stability criterion to satisfy stable navigation:

$$v\, d_t \leq \delta / \cos\alpha \tag{1}$$

In Equation 1, v is velocity, dt is the time step size, and α is the angle between desired path and desired course. Equation 1 implies that the position change of the USV in each time step must be equal to or lesser than the distance between the virtual target point and the current position of the USV. It means the actual position of the USV in the next time step must be on the predefined path or between the last position of the USV and the predefined path. Otherwise, the navigation of the USV is unstable. Equation 2 shows the minimum distance of δ to satisfy stable navigation.

$$\delta \geq v\, d_t \cos\alpha \tag{2}$$

The value of α, which maximizes the right-hand side in Equation 2, is zero. In that case, stability criterion is expressed as following Equation 3.

$$\delta \geq v\, d_t \tag{3}$$

In this study, it is supposed that the velocity of the USV is 20 meter per second and time step size is 0.5 second. In this case, the right hand size in Equation 3 is 10 meter for each time step. The δ value must be equal to 10 meter or greater than 10 meter in order to obtain a stable navigation.

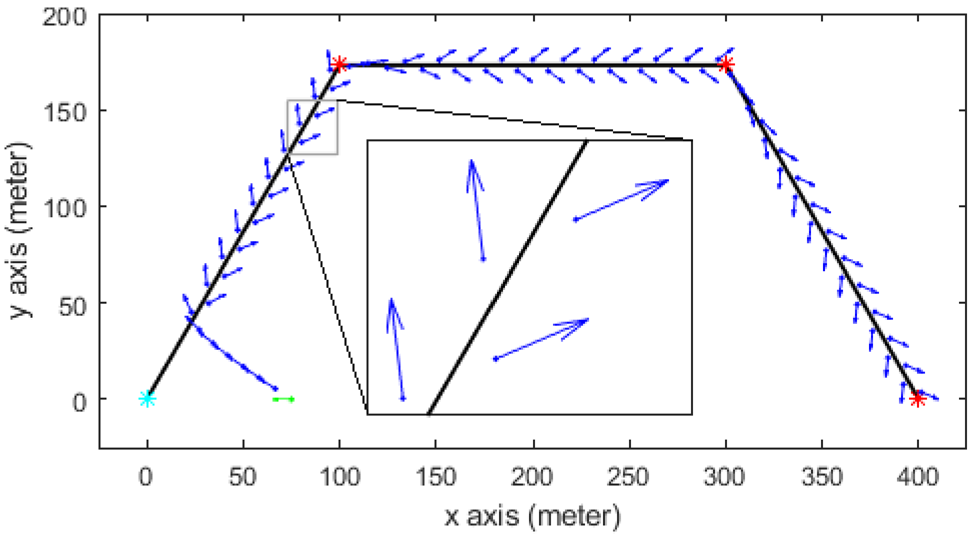


**Figure 2.** An unstable navigation for δ=4 meter with unlimited turning rate.

Figure 2 shows an unstable navigation for δ value is equal to 4 meter for every time step. On the other hand, Figure 3 shows a stable navigation for δ value is equal to 11 meter.

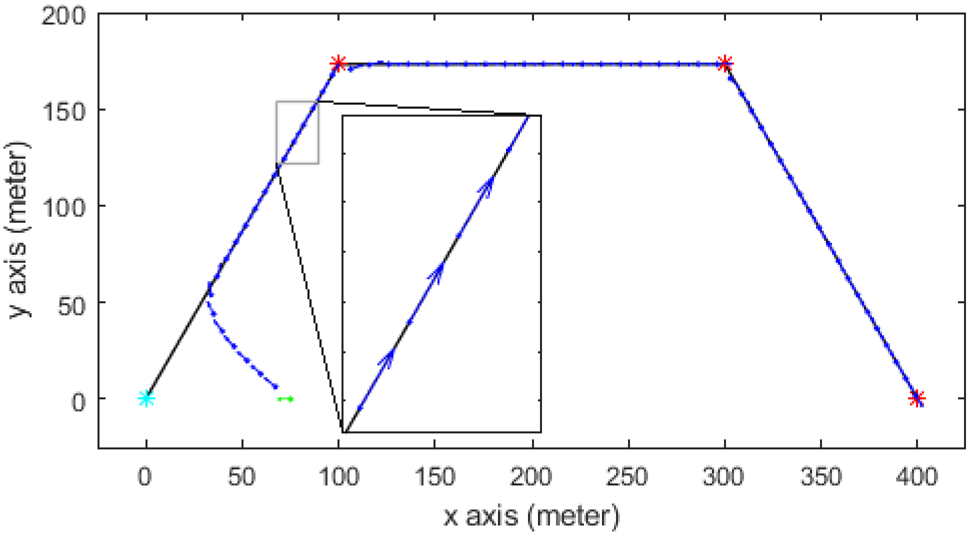


**Figure 3.** A stable navigation for δ=11 meter with unlimited turning rate.

One another important parameter for a realistic and stable navigation is the limit of turning rate of the USV in each time step. Figure 4 shows a stable and realistic navigation using δ value is 11 meter and the maximum turning rate is 20 degrees per second.

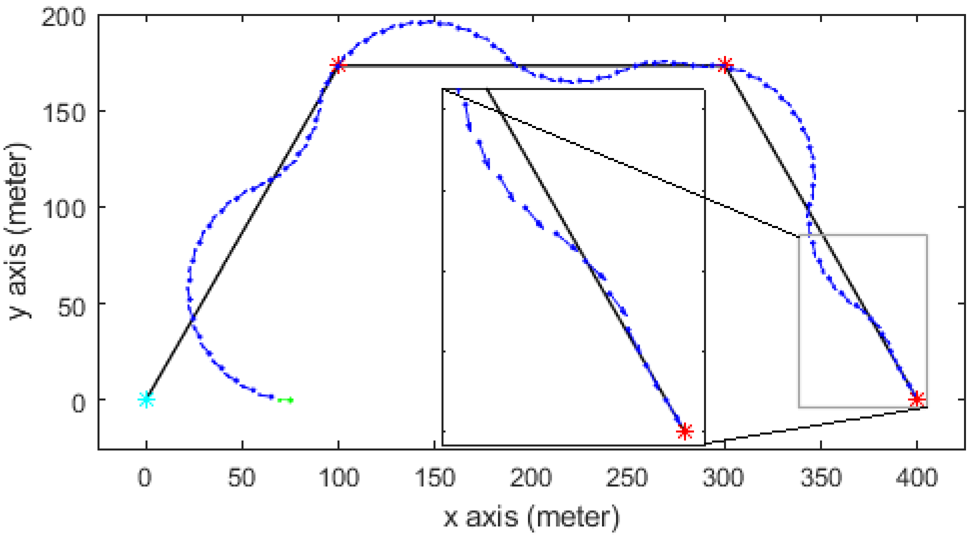


**Figure 4.** A stable and realistic navigation (δ=10 meter and maximum turning rate=20 deg/s).

Secondly, this study proposes a flexible δ value instead of the fixed δ parameter to get an optimum, accurate, stable and realistic navigational path. Equation 4 shows proposed flexible δ value:

$$\delta \geq v\, d_t(1 + tr/tr_{max}) \tag{4}$$

In Equation 4, tr represents the turning rate of the USV using current course angle, previous course angle and time step size. $tr_{max}$ is a saturation and it represents maximum turning rate of the USV to simulate a realistic navigation. Figure 5 indicates an optimum, stable and realistic navigation using flexible δ value.

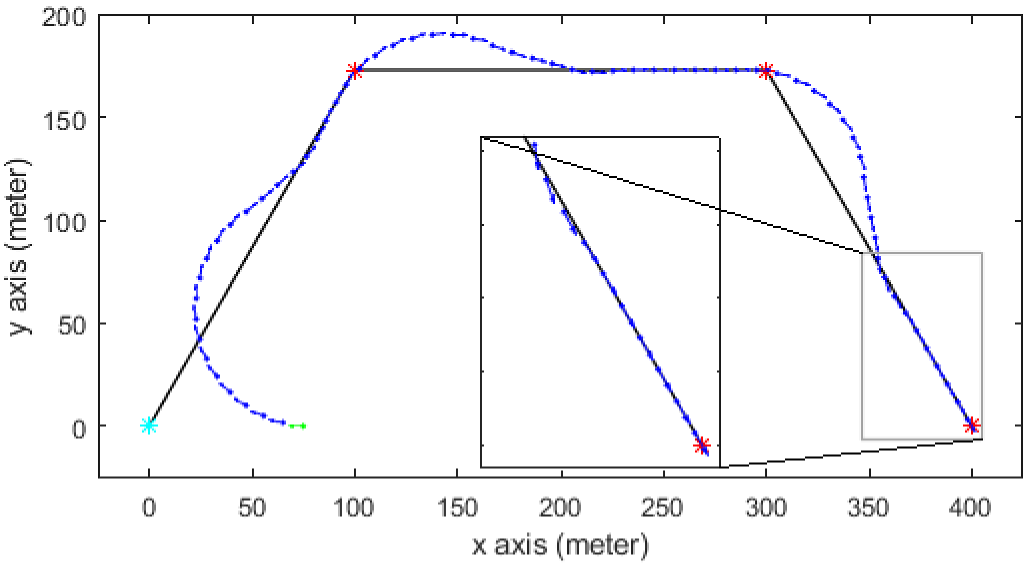


**Figure 5.** An optimum and stable and realistic navigation using flexible δ value (maximum turning rate=20 deg/s).

## 3. Findings and Discussion

In this section, it is supposed that velocity of the USV is 10 meter per second, maximum turning rate is 20 degrees per second, total simulation time is 100 second, time step size is 0.5 second, and initial course angle of the USV is 90 degrees. Initial position of the USV is (160,0) in coordinate system and four different target points are selected for navigation namely (0,200), (160,320), (320,200) and (320,0). In order to minimize tracking errors during autonomous navigation, the δ parameter needs to be optimized. The optimum δ value varies according to the maneuverability of the autonomous vehicle and the distance of the autonomous vehicle to the desired route. For this reason, using a fixed δ value, as in previous studies, increases the tracking errors significantly. Choosing the δ value too small than the optimum value causes stability problems and makes cross tracking errors unacceptable (red colored navigation in Figure 6, δ=2.5 meter). Although USV catches the predefined path immediately, it makes an aggressive navigation like a snake by crossing to the opposite side of the road. On the other hand, choosing the δ value higher than the optimum value causes the autonomous vehicle to travel far from the desired route (green colored navigation in Figure 6, δ=50 meter), again increasing the tracking errors. Therefore, determining the optimum δ value for each time step reduces tracking errors.

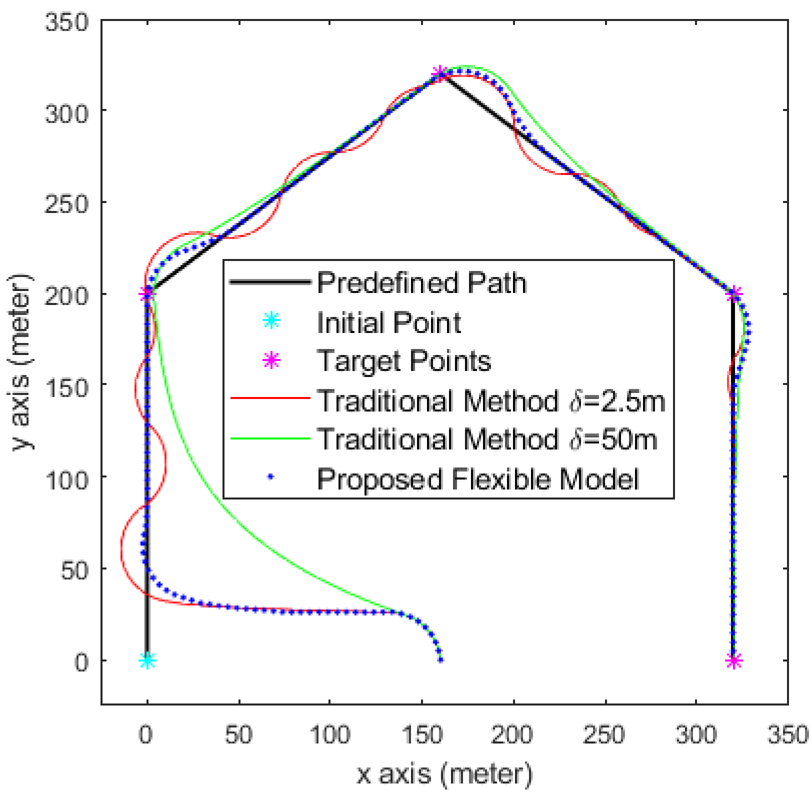


**Figure 6.** Advantage of flexible model over the traditional technique.

In Figure 6, unlike conventional methods, proposed flexible model (blue circles) determines the optimal navigational parameter and it adjust the δ value according to velocity, maximum turning rate and position of USV. Table 1 shows tracking errors for different δ parameters and the proposed flexible model. This study proposes an algorithm that can determine the optimum sigma values for each time step. According to Table 1, the proposed Flexible Algorithm decreases tracking errors significantly compared to the conventional carrot chasing algorithm used a fixed δ value.

**Table 1.** Tracking errors (meter) for different navigations.

| | Tracking Error (m) | Error Percentage (%) |
|---|---|---|
| δ=2.5 m (δ<stability criteria) | 3784.6 | 13.7 |
| δ=5 m (δ=stability criteria) | 3442.5 | 3.4 |
| δ=15 m (δ>stability criteria) | 3386.2 | 1.7 |
| δ=25 m (δ>stability criteria) | 3522.2 | 5.8 |
| δ=35 m (δ>stability criteria) | 3721.1 | 11.8 |
| δ=45m (δ>stability criteria) | 3849.4 | 15.6 |
| δ=50 m (δ>stability criteria) | 4024.9 | 20.9 |
| Proposed flexible δ value | 3329.1 | - |

## 4. Conclusion

In previous studies related to the carrot chasing algorithm, fixed δ parameters have been used. In this study, it is observed that using the fixed δ value is not convenient for every position of the USV on the navigation map and the fixed δ parameter is not appropriate for USVs which have different maneuverability (maximum turning rate). This study firstly proposes the stability criterion in order to limit the minimum δ value for stable and realistic navigation. Secondly, this paper presents a smooth, accurate as well as stable path following algorithm using the proposed stability criterion. When compared to the traditional carrot-chasing algorithm used fixed parameters (δ=2.5m, δ=5m, and δ=50m), the proposed innovative model reduces tracking errors by roughly 14%, 3% and 20% respectively. Using the turning rate data from the previous time step, this algorithm determines the unique target points for each time step. During the sharp turning movements, it enables smooth and precise navigation. The proposed model has also saturation for the highest possible turning rate, allowing for realistic navigation. Moreover, this study also presents a numerical simulator for USVs in the Matlab environment so that alternative path following algorithms can be compared. It is possible to adjust the number and position of waypoints, the USV's initial course angle, and the USV's initial position and velocity in this simulator. Finally, all Matlab codes related to the numerical simulator have been added to this paper to facilitate other researchers' work.


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### Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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## Appendix

```
clc,clearvars,close all

%Input Data
W0=[0,0]; W1=[0,200]; W2=[160,320]; W3=[320,200]; W4=[320,0];
W=[W0;W1;W2;W3;W4];%positions of waypoints (m)
p=[160,0];%position of usv (m)
v=10;%velocity of usv (m/s)
psip=90;%course angle of usv (degree)
tr_max=20;%max turning rate of usv (degree/s)
tt=100;%total simulation time (s)
dt=0.5;%time interval (s)
cc=0.001; %cos(a) convergence criteria
bk=1000; %break criteria for while loop

%Output Data
j=1;
d=NaN; phi(1:length(W))=NaN; pp=NaN; pp(1,1:2)=p;
plot(p(1),p(2),'go','markerfacecolor','g','MarkerSize',1.8)
hold on
plot(W(1:end,1),W(1:end,2),'k','lineWidth',1.5)
plot(W(1,1),W(1,2),'c*')
% quiver(p(1),p(2),cosd(psip),sind(psip),80,'g','MaxHeadSize',2)
for i=1:length(W)-1
phi(i)=atan2d((W(i+1,2)-W(i,2)),(W(i+1,1)-W(i,1)));
for t=0:dt:tt
Ru=sqrt((W(i,1)-p(1))^2+(W(i,2)-p(2))^2);
phiu=atan2d((W(i,2)-p(2)),(W(i,1)-p(1)));
beta=phi(i)-phiu;
R=abs(Ru*cosd(beta));
d(j)=abs(Ru*sind(beta));

csap=1;
tr=0;
diff_csa=1;
k=1;
while diff_csa>cc
delta=v*dt*csap*(1+tr/tr_max);
if d(j)/v*0.6<=abs(phi(i)-psip)/tr_max; delta=delta/csap; end
% delta=50;
vtp=[W(i,1)+cosd(phi(i))*(R+delta),W(i,2)+sind(phi(i))*(R+delta)];
psi=atan2d((vtp(2)-p(2)),(vtp(1)-p(1)));
tr=abs(psi-psip)/dt;
csa=delta/sqrt(delta^2+d(j)^2);
diff_csa=abs(csa-csap);
csap=csa;
k=k+1;
if k>bk; break; end
end
% disp(k)

if tr>tr_max && psi>psip; psi=psip+tr_max*dt; end
if tr>tr_max && psi<psip; psi=psip-tr_max*dt; end
p=[p(1)+v*cosd(psi)*dt,p(2)+v*sind(psi)*dt];
pp(j+1,1:2)=p;
psip=psi;
```

```
j=j+1;

% set(gcf, 'Units', 'Normalized', 'OuterPosition', [0 0 1 1]);
plot(W(i+1,1),W(i+1,2),'r*')
plot(p(1),p(2),'bo','markerfacecolor','b','MarkerSize',1.8)
% quiver(p(1),p(2),cosd(psi),sind(psi),80,'b','MaxHeadSize',2)
axis equal
xlim([-25 350])
ylim([-25 350])
xlabel('x axis (meter)')
ylabel('y axis (meter)')
set(gcf, 'Color', 'white')
% hold off
pause(0.1)
if sqrt( (p(1)-W(i+1,1))^2 + (p(2)-W(i+1,2))^2)<v*dt; break; end
end
end
disp(sum(d))
```