Performance comparison of various navigation guidance methods in interception of a moving object by a serial manipulator considering its kinematic and dynamic limits

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***Abstract*— In this paper a comparative analysis is represented on various navigation guidance methods used for intercepting fast maneuvering moving objects. A glancing revision is introduced on relevant works within the introduction section. Four common methods for navigation guidance known as PNG, APNG, IPNG and AIPNG are under investigation. Results demonstrate their infirmity on smoothly intercepting a moving object. Hence, to improve the navigation guidance methods and to adapt them with robotic problems a modified version of AIPNG is proposed for 2D problems and is developed for 3D problems utilization.**

I. INTRODUCTION

Interception of a moving object can be discussed in two different classes based on the objects' velocity[1];

1. Object with slow maneuvering motion,
2. Object with fast maneuvering motion.

A slow maneuvering motion is usually known as a constant velocity or a motion with small acceleration magnitudes. Therefore, a reliable anticipation can be derived on the objects motion and furthermore time optimal methods can be presented for object interception[2, 3]. Unlike slow maneuvering objects, during a fast maneuvering motion, abrupt trajectory variation occurs frequently and as a result practical predictions are impossible.

In another point of view catching a moving object using a serial manipulator can be classified to four categories as follow:

3. Trajectory regeneration methods
4. Navigation Guidance methods
5. Visual servoing methods
6. Potential field methods

Considering the first class, systems are constituted of a separate trajectory planning section. This section plans the desired path considering the robot position and objects predicted position. The desired trajectory will be regenerated continuously for the new conditions. These methods are known as Prediction, Planning and Execution methods (PPE or APPE) and are suitably functional in case of objects with slow maneuverability [4].

A widely used method for intercepting fast-maneuvering moving objects falls under the category of navigation and guidance theory. Navigation-based techniques were originally developed for the control of missiles tracking free-flying targets. In these methods the strategy of interception is expressed as closing the interceptor and objects distance and guiding the object to a collision course with the target by enforcing an acceleration vector to the interceptor. Accelerator magnitude and direction is computed based on the objects velocity and position vectors [4, 5].

Visual servoing methods, however, do not possess any trajectory planning section. The controller block attempts to eliminate the velocity and position error between the interceptor and the target utilizing prevalent control schemes. Because of their computational efficiency, such methods are well suited for tracking fast-maneuvering objects[6, 7]. Vision systems are commonly used as feedback sensors in order to produce essential environmental information.

Fourth category is called the potential field method and is enumerated as a common method in catching objects in presence of obstacles[8].

Navigation Guidance Based Interception

This method has been used for tracking of free flying objects through last 5 decades. The most important application for this method is guiding missile to aim another free flying objects like airplanes or rockets.

Several navigation guidance laws are presented until now. PNG is the most common law that has been well analyzed and evaluated recently [9, 10]. Widespread researches present PNG as a time-optimal solution for intercepting object with constant velocity. In [11-13], it is demonstrated that PNG method loses the quality of being time-optimal, in case of objects evading with a accelerating

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motion. Bryson et al, [11], showed that PNG can cope with a maneuvering target by simply tuning the guidance gain.

An alternative to PNG law for fast-maneuvering targets has been developed as Augmented Proportional Navigation Guidance (APNG) [11]. This technique yields a time-optimal solution for intercepting fast-maneuvering targets under the following conditions:

1. Both the interceptor and the target can only maneuver in the direction normal to their instantaneous velocity
2. The average acceleration of the target is known and available to the guidance control system.

Many have modified the PNG law to fit for inconstant object velocity or acceleration situation [12, 14]. Yuan et al, [14], reported a new guidance scheme of Ideal Proportional Navigation Guidance (IPNG). This technique shows better mathematical tractability and less sensitivity to pursue and evasion problem's initial conditions with respect to the PNG-based navigation techniques. Its capture criterion is solely defined by the navigation gain and does not depend on the initial conditions. It has been shown that this technique is similar to the PNG when the interceptor has considerable speed superiority over the target[15].

As mentioned earlier, navigation techniques have been used in the past for on or offline generation of paths in non-robotic environments and only recently in mobile robotics [1].

In order to apply the navigation guidance techniques to serial robotic systems, manipulator limits needs to be considered. Chaw et al, [4], performed an actuator limit transformation from joint space to the robots working space. Hence, permissible acceleration applied to the robot can be checked and restricted beforehand.

In addition, unlike a missile interception, robotic interception needs to be smooth. The velocity of the robot and the moving object must match at the rendezvous for a smooth grasping. Mehrandezh et al [1], proposed a hybrid interception scheme, which combines a navigation-based interception technique with a conventional trajectory tracking methods.

Chaw et al, [4], yielded another approach to overcome this problem. They separated the tangential acceleration from the normal one and used two different laws for each.

In this paper we will evaluate and compare various techniques regarding to navigation guidance methods. We will discuss Chaws approach and generalize it to be applicable in 3D interceptions.

II. Proportional Navigation Guidance and Augmented Proportional navigation guidance method

In a conventional PNG method the acceleration applied to the end-effector is normal to interceptors' velocity vector and is generated according to the following law.

$$\vec{a}_{PNG} = \lambda \vec{V}_i \times \vec{\omega}_{LOS} \quad (1)$$

Where λ is the navigation gain, $\vec{V}_i$ denotes the interceptor's velocity vector and $\vec{\omega}_{LOS}$ denotes the angular rate of the Line of Sight (*LOS)* (Figure 1).

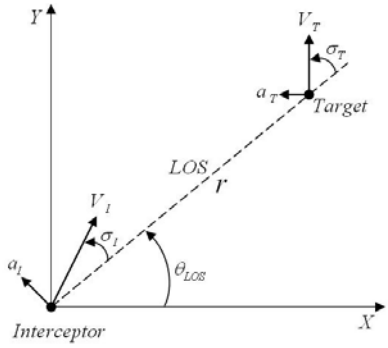

Figure 1. Schematic diagram for a 2D pursue and evasion system

Ha et al. [16] showed that in situations which the target's acceleration is piecewise continuous and is upper bounded with a known constant, $|a_T(t)| \le \alpha$, the PNG law given in Equation(1) always intercepts the target under the following conditions:

$$\begin{aligned}
&(1)\quad |\rho \sin\sigma_T(0) - \sin\sigma_I(0)| \le \beta \ \text{ for some constant } \beta \in \{0, 1-\rho\}, \\
&(2)\quad |\sigma_I(0)| < \frac{\pi}{2}, \\
&(3)\quad \text{The navigation gain is choosen so that:} \\
&\qquad \lambda > 1 + \frac{\rho + \alpha r(0) / (\beta |V_I(0)|^2)}{\sqrt{1 - |\rho + \beta|^2}}.
\end{aligned} \quad (2)$$

Where ρ is defined as $\rho = \frac{|V_T(0)|}{|V_I(0)|} < 1$, and σ_T and σ_L are the angles between target's and interceptor's velocity with the *LOS*, respectively. Applying Lyapunov method, they also showed that there exists a finite time, T_f , such that

$$T_f < \frac{r(0)}{|V_I| \sqrt{|1-\rho|^2 |\beta|^2}},$$
$$r(T_f) = 0,$$
$$r(t) \le r(0) \ \ \forall t \in [0, T_f].$$

It should be noted that, if condition (2) is not satisfied, then it is not guaranteed that $r(t) \le r(0)$.

If objects acceleration differs from what mentioned before, PNG is no longer reliable. An augmented PNG method is proposed for such conditions. A new term of objects acceleration is added to PNG law and APNG law is reformed as:

$$a_{APNG} = \lambda |V_I \times \omega_{LOS}| + \lambda/_2 |a_T| \quad (3)$$

The above acceleration command is applied in a direction defined by $\vec{V}_I \times \vec{\omega}_{LOS}$. The $\frac{\lambda}{2} a_T$ term will compensate any deviation caused by objects acceleration.

III. IDEAL PROPORTIONAL NAVIGATION GUIDANCE AND AUGMENTED IDEAL PROPORTIONAL NAVIGATION GUIDANCE

Ideal Proportional Navigation Guidance (IPNG) is an improvement over the conventional. In IPNG, the acceleration command is applied in a direction normal to the relative velocity between the interceptor and the target, rather than normal to the interceptor's velocity as in the PNG law. Furthermore, its magnitude is proportional to the product of *LOS* angular rate and the relative velocity.

$$\vec{a}_{IPNG} = \lambda(\vec{V}_T - \vec{V}_I) \times \vec{\omega}_{LOS}. \quad (4)$$

The advantage of IPNG is in its minor sensitivity to initial conditions with respect to PNG. Objects are more guaranteed to be caught in this method. Therefore, IPNG is a more suited method for robotic utilization.

Yuan et al. [14] showed that interception is indispensable if $\lambda > 1$, and *LOS* angular rate approaches zero if $\lambda > 2$ for cruising targets.

When the interceptor has absolute speed superiority over the target, then, PNG and IPNG become similar [15]. The performance of PNG depends on the value of $\rho = \frac{|V_T(0)|}{|V_I(0)|} < 1$. If $\rho \to 0$, then, the PNG formula converge to that of the IPNG

$$\lim_{\rho \to 0} PNG = IPNG. \quad (5)$$

It can be shown that when *LOS* angular rate approaches zero, then, the relative velocity between the target and the robot has to lie on the *LOS* [15]. This causes the dimensionality of the interception problem to reduce to one. This characteristic of the IPNG, especially, makes it attractive for robotic interception. Mehrandezh showed that reduction in dimensionality can also improve the time of intercepting.

IPNG can also get more enhanced by adding a term of object acceleration to IPNG law. The law derived is known as AIPNG and is as follow

$$a_{APNG} = \lambda\left|(\vec{V}_T - \vec{V}_I) \times \vec{\omega}_{LOS}\right| + \lambda/_2 |\vec{a}_T| \quad (6)$$

Similarly, this acceleration command must be applied in a direction defined by $(\vec{V}_T - \vec{V}_I) \times \vec{\omega}_{LOS}$.

IV. MODIFYING AIPNG AND ACHIEVE A SMOOTH CATCHING.

As mentioned, chaw proposed a modified version of AIPNG to improve the smoothness of interception. This method is imitate of a proposed method in [16] and is adjusted for robotic applications. In this method two acceleration commands are applied separately in orthogonal body axis directions.

Two axes will determine for this problem, inertia and body axis. Inertia axis is firm and is used normally to describe the position of end-effectors. The X direction of the body axis is the moving direction of the robot arm and Y direction is orthogonal to X direction. Figure 2 and 3 shows these two axes for a 2D planar robot.

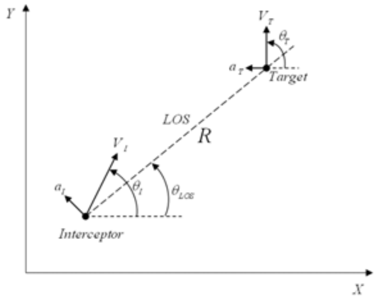

Figure 2. Schematic diagram of the pursuit and evasion problems parameters

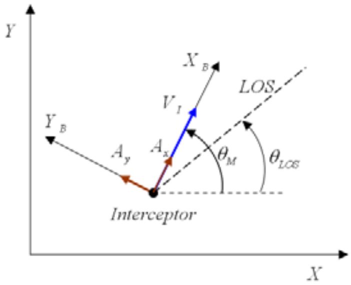

Figure 3. Schematic figure of accelerations enforced on the interceptors

Two separate acceleration commands are exploited in tangential and normal directions to guide the interceptor toward the object. The normal acceleration makes the interceptor velocity to lie on *LOS* and the normal acceleration decreases the distance between them on the LOS. We used the guidance law suggested in [17] for the normal acceleration which the equation is

$$A_{y_B} = a\frac{d\theta_{LOS}}{dt} + b\sin(\theta_{LOS} - \theta_I). \quad (7)$$

In the corresponding equation the term of $b\sin(\theta_{LOS} - \theta_I)$ causes the reduction in deviation angle between interceptor velocity and *LOS* and $a\frac{d\theta_{LOS}}{dt}$ reduce the sensitivity of interceptor to changes of θ_{LOS}.

An acceleration command in X direction of the body axis is needed to decrease the distance between the interceptor and the target. Following law is used for this purpose.

$$A_{x_B} = k_p R + k_d V + A_{T_X} \quad (8)$$

Where R and V are the relative distance and velocity of interceptor and object in LOS direction, respectively. A_T is the X component of the object acceleration in the body axis and k_p and k_d is position and velocity gains. Figure 3 also shows the state of applying the accelerations.

V. PROOF OF CONVERGENCE

To illustrate the convergence of interceptor with the target in this method we will study the effect of the proposed law on pursue and evasion system. Considering the interceptor's motion we have,

$$\vec{V}_I = V_I \hat{i}. \tag{9}$$

Thus, interceptor's acceleration can be derived as follow,

$$\vec{A}_I = \dot{V}_I \hat{i} + V_I \theta_I \hat{j}. \tag{10}$$

Substituting equation (10) in the Y component of body axis acceleration law we'll have

$$V_I \dot{\theta} = a\dot{\theta}_L + b\sin(\theta_L - \theta_I). \tag{11}$$

Assuming $a = V_M$ we'll reach to

$$V_M(\dot{\theta}_L - \dot{\theta}_I) + b\sin(\theta_L - \theta_I) = 0. \tag{12}$$

Defining $\sigma_M = \theta_L - \theta_I$ and $\gamma = b/V_M$ and replacing them in equation 12 we'll have

$$(\dot{\sigma}_I) + \gamma\sin(\sigma_I) = 0. \tag{13}$$

A solution to this differential equation is expressed as;

$$\frac{1-\cos\sigma_I}{\sin\sigma_I} = e^{-\gamma t} \tag{14}$$

It is obvious that in equation 14 while $t \to \infty$ then $\sigma_I \to 0$ guarantying that the interceptor's velocity will eventually lies on the *LOS*.

Further in this section we will discuss the tangential convergence of the proposed method.

It can easily be shown if $\sigma_I = \theta_L - \theta_I = 0$, tangential acceleration can be expressed as

$$A_{T_X} = A_X + \ddot{R} - R\dot{\theta}_L^2 \tag{15}$$

Substituting equation (15) in equation 8 we'll have

$$\ddot{R} + K_d\dot{R} + (K_p - \dot{\theta}_L^2)R = 0. \tag{16}$$

Through a direct intuition one can say that $\dot{\theta}_L$ will be zero. Through analytical viewpoint due to A_y and interceptor nonzero velocity we can see that

$$\left|\dot{\theta}_L\right| = \left|\frac{A_y}{a}\right| = \left|\frac{A_y}{V}\right| < \infty. \tag{17}$$

Now if we choose

$$K_p = \alpha + \dot{\theta}_L^2, \tag{18}$$

Equation 16 converts to

$$\ddot{R} + K_d\dot{R} + \alpha R = 0. \tag{19}$$

In equation (19) if K_d and α are selected positive, R will asymptotically converge to zero.

VI. Extending the proposed Method to 3D

In 3D problems we use equations (20) and (21) as a replacement for acceleration equations (7) and (8).

$$A_x = k_p R + k_d \dot{R} + A_{T_X} \tag{20}$$

$$A_n = (a\frac{d\theta_{LOS}}{dt} + b\sin(\alpha))\hat{n} \tag{21}$$

Where α defines the spatial angle between interceptor's velocity and *LOS*. A_x and A_n are tangential and normal acceleration applied in $\hat{v}$ and $\hat{n}$ directions which are defined by

$$\hat{v} = \frac{\vec{V}_I}{|\vec{V}_I|} \text{ and } \hat{r} = \frac{\vec{R}}{|\vec{R}|},\ \hat{n} = (\hat{v}\times\hat{r})\times\hat{v}. \tag{22}$$

α's value can be computed from

$$\alpha = \cos^{-1}(\hat{v}.\hat{r}). \tag{23}$$

VII. Modifying acceleration command to satisfy actuator limits

Actuators must be able to generate the torque and velocity which is needed to produce the desired acceleration. Consequently actuators torque and velocity magnitude must lay in the permissive area defined for the actuator.

Joints velocities can be obtained using End-effector's velocity and robot's inverse jacobian.

$$\dot{r} = J\dot{q} \Rightarrow \dot{q} = J^{-1}\dot{r} \tag{24}$$

Joints acceleration is yielded from the derivation of equation (24), so we have

$$\ddot{q} = -(J^{-1}\dot{J}J^{-1})\dot{r} + J^{-1}\ddot{r}. \tag{25}$$

Considering robot dynamics equation as follow

$$M(q)\ddot{q} + H(\dot{q},q) = \tau, \tag{26}$$

The maximum velocity and acceleration for the end-effector can be derived as follow

$$\dot{r}_{\max} = J\dot{q}_{\max} \tag{27}$$

$$\ddot{r}_{\max} = J(M^{-1}(\tau_{\max} - H) + (J^{-1}\dot{J}J^{-1})\dot{r}) \tag{28}$$

VIII. Simulation Results

Methods mentioned above, have been applied to two different systems, one with a target moving with constant velocity and one with a target moving with variable velocity. A 5 DOF robot is utilized in these simulations. (Fig (4)) Simulation results are presented as shown in table 1.

TABLE I. TABLE 1. How simulation results are planned

Target's maneuver	Constant velocity	Variable velocity	
Compared Methods	*PNG, IPNG, APNG, AIPNG*	*AIPNG and modified AIPNG*	*PNG and IPNG*

IX. Results

A. Simulation 1: Comparing PNG and IPNG methods

In this example, the target moves with a constant speed. The initial condition for this example is given in table 2. It can be shown that these conditions satisfy equation (2).

TABLE II. INITIAL CONDITIONS FOR SIMULATION 1

Initial conditions		End-effector	target
Position	x	0.39	0.15
	y	0	0.15
	z	0.5	0
Velocity	$\dot{x}$	-0.2	0.1
	$\dot{y}$	0.2	0.1
	$\dot{z}$	0.1	0.1
Acceleration	$\ddot{x}$	0	0
	$\ddot{y}$	0	0
	$\ddot{z}$	0	0

Figure 4 compares the approaching trajectories for PNG and IPNG method. Relative distance and the relative speed vector's magnitude are shown in figure 5 and 6.

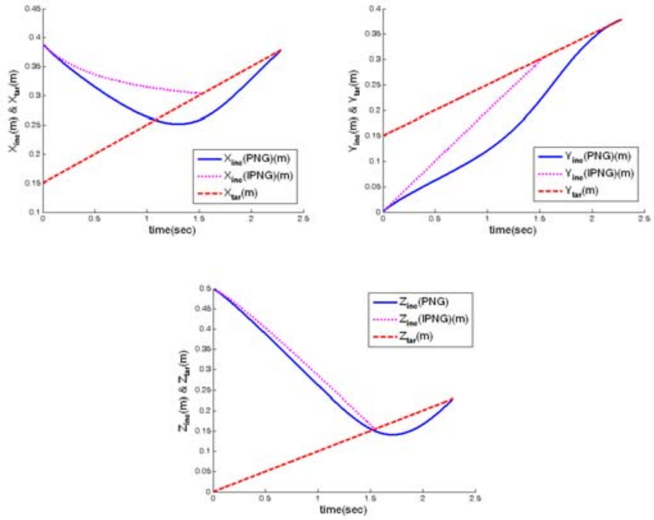

Figure 4. Variation of robot and target's position

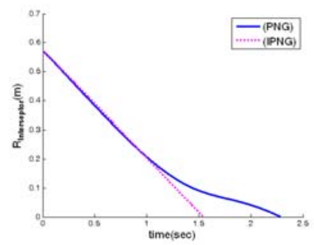

Figure 5. Magnitude of interceptor and targets distance

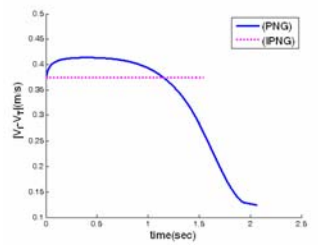

Figure 6. Magnitude of interceptor and target's relative velocity vector

Simulation results indicate that such an initial condition both of the methods succeed in catching the target. It can also be seen that the IPNG method gives out better results due to the less catching time. From the variation of relative velocity diagram (figure 6), it can be perceived that neither of the methods leads to a smooth catching.

B. Simulation 2: Comparing PNG, APNG, IPNG and AIPNG methods

In this section the result of catching a target with variable speed is presented from figure 7 to 9, and the diagrams are organized just like the last example. Initial condition for this simulation is as table 3

TABLE III. INITIAL CONDITIONS FOR SIMULATION 2

Initial conditions		End-effector	target
Position	x	0.3	0.15
	y	0.3	0.15
	z	0.3	0
Velocity	$\dot{x}$	-0.2	0.1
	$\dot{y}$	0	0.1
	$\dot{z}$	0	0.1
Acceleration	$\ddot{x}$	0	$0.2\sin(4t)$
	$\ddot{y}$	0	$0.6\sin(4t)$
	$\ddot{z}$	0	$0.2\sin(4t)$

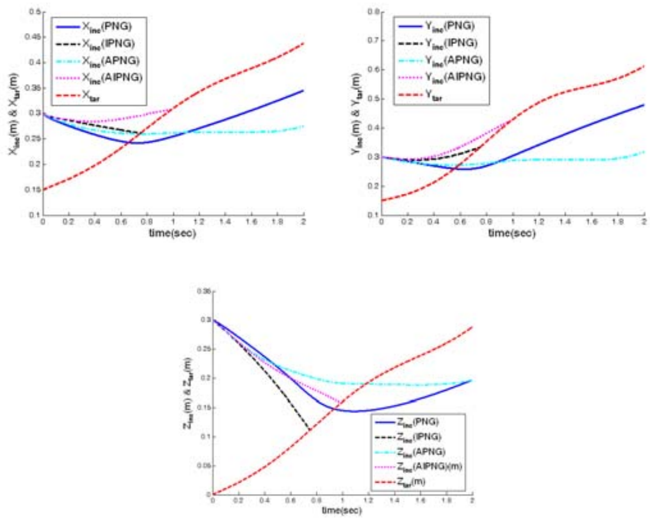

Figure 7. Variation of robot and target's position

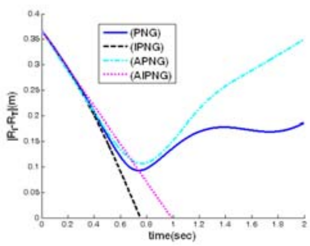

Figure 8. Magnitude of interceptor and targets distance

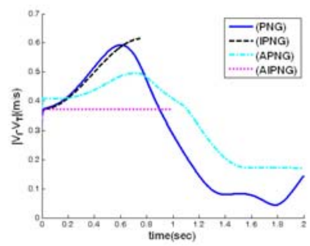

Figure 9. Magnitude of interceptor and target's relative velocity vector

For the above initial condition, PNG and APNG methods are incapable of catching the target. This is occurred due to interceptor's low initial speed of and in addition the obtuse angle between initial speeds of interceptor and target. IPNG and AIPNG are acting approximately the same. However, this can't be a general conclusion while IPNG can't follow and catch a target with bigger accelerations. All in all, the AIPNG has the best functionality among other methods; however, none of them can catch the object smoothly.

C. *Simulation3: Comparing AIPNG and its modified version*

Applying simulation 2 initial condition to AIPNG and the modified AIPNG method, the following results are obtained as shown in figure 10 to figure 12.

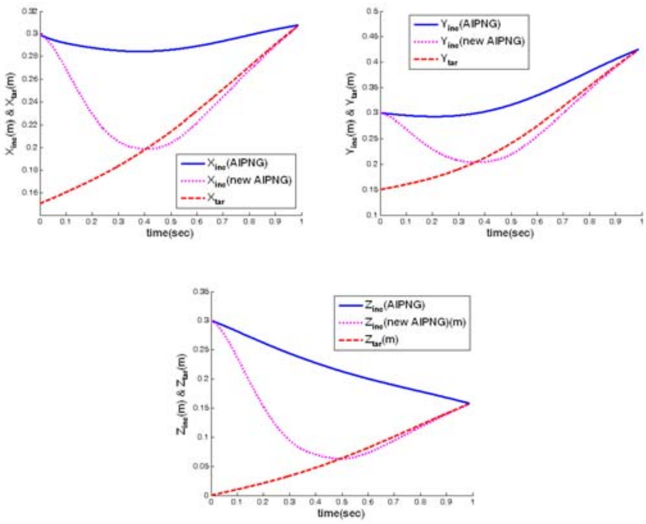

Figure 10. Variation of robot and target's position

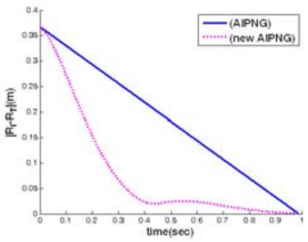

Figure 11. Magnitude of interceptor and targets distance

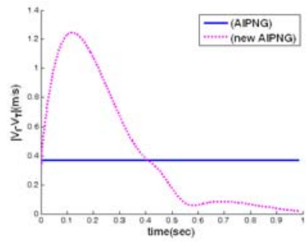

Figure 12. Magnitude of interceptor and target's relative velocity vector

Results exhibits that however modified AIPNG method consumes more time for catching the object, it can catch the object quite smooth, unlike other presented methods.

X. CONCLUSION

this paper various navigation guidance methods was examined on catching a moving objects with a manipulator. Among all methods, IPNG and AIPNG methods showed better results due to their low energy consumption and speed of catching. All of these methods lead to a collisional catching. To modify the defection we presented the modified AIPNG method. The energy consumed in this method rises up which an optimization algorithm is suggested to moderate the energy intake.

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