2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Cooperative Guidance for Simultaneous Interception Using Multiple Sliding Surfaces

Maximillian Fainkich[1] and Tal Shima[2]

***Abstract*— A cooperative guidance strategy is developed to force multiple interceptors to intercept a target simultaneously. The guidance law works to minimize the time-to-go difference between neighboring interceptors while still keeping the interceptors on track for interception. The guidance law is derived using sliding mode control, with one sliding surface for every pair of neighboring interceptors to remove time-to-go difference and one global sliding surface to make sure at least one interceptor is heading towards the target, guaranteeing the others as well. A time-to-go approximation scheme for a stationary target is used during the derivation. A two-dimensional nonlinear simulation of the relative kinematics is run for cases of both two interceptors and more, in which the guidance law is shown to successfully cause simultaneous interception between multiple interceptors starting from different initial conditions.**

I. INTRODUCTION

One possible idea for a cooperative guidance law is to have multiple interceptors arrive simultaneously to the target. Having multiple interceptors arrive at the target at the same time makes evasion much more difficult, as the target cannot evade each interceptor one at a time, but must focus on all of the interceptors at once. Even if the target is not moving, this strategy also challenges missile defense systems, which struggle with large amounts of enemies to deal with at once. In addition, arrival of multiple interceptors to a target can increase the damage and effect by combining multiple warhead delivery. Having the ability for the interceptors to create a simultaneous interception scenario in midair increases operability by removing the need for coordination between the two launch sites beforehand.

The problem of having multiple missiles arrive at the same place at the same time has been explored in the literature. Most research in simultaneous interception is based on impact time guidance, where the missiles are told to arrive at the target at a specific time regardless of the other missiles in the encounter. Impact time guidance has been extensively explored in the literature. In [1], a term is added to the normal proportional navigation (PN) expression based on the difference between the calculated range-to-go of the interceptor and the desired range-to-go of the impact time. In [2] and [3], a sliding mode controller is used in order to achieve the same goal, with the sliding surface dependent on the difference between the estimated and required final times. The problem is also solved using a Lyapunov control in [4], where the controller causes both interception at a specified time and simultaneous interception of multiple interceptors.

Impact time guidance can easily be used to cause two interceptors to simultaneously intercept a target by defining the same desired time of interception. The simplest method of achieving this is noncooperative, where the impact time of all interceptors is predefined. This method is applied in [5], where impact time guidance is achieved by switching the navigation gain of PN to affect the time-to-go, and is then extended to apply to simultaneous interception. The same method is applied in [6], where a Lyapunov based guidance law is developed for impact time guidance and then again extended to achieve simultaneous interception, in [7], [8], where a sliding mode control is implemented for impact time guidance, and also in [9] where a supertwisting control is used. While generally effective, cooperative methods may be more adaptable to disturbances in the encounter as the different interceptors account for each other, instead of just themselves.

Desired impact time can also be updated on the fly for a more cooperative approach, improving performance by allowing multiple interceptors to respond to disturbances that occur during the flight and guaranteeing simultaneous interception for a more dynamic environment. This problem has also been relatively well explored in the literature. In [10], a term is added to the PN expression that includes a time-varying gain based on the time-to-gos of the given interceptor and the other interceptors, bringing the time-to-gos into convergence with one another. Similar to this work, an extension to PN is made in [11] based on the time-to-go difference and it is tested for various approximation schemes for the time-to-go. In [12], the problem is split into two directions, with a sliding mode based on the time-to-go difference between interceptors being used in the line of sight (LOS) direction to cause simultaneous interception, and a sliding mode in the direction perpendicular to the line of sight being used to control intercept angle, with the interceptors having variable speed instead of constant speed.

Some methods besides impact time guidance have also been successful in bringing simultaneous interception. In [13], simultaneous interception is achieved by predefining a formation throughout the encounter that leads to simultaneous interception and staying on that formation. In addition, a second strategy is proposed in [14] of setting the other interceptor as the target, but driving all heading errors to zero so that the interception of the other interceptor occurs at the real target. In [15], the interceptors follow momentarily circular trajectories, exchange information cyclically, and

[1]Graduate Student, Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, 3200003 Haifa, Israel maxf1000@gmail.com
[2]Professor, Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, 3200003 Haifa, Israel tal.shima@technion.ac.il

enlarge their trajectory when their minimum impact time is smaller than that of their neighbor's, gradually bringing all interceptors to intercept the target simultaneously. In [16], where the guidance law is split into two stages; the first stage involves the interceptors moving to a set of initial conditions which will lead to simultaneous interception, namely the same range and magnitude of LOS angle, before moving to the second stage which is normal PN. Despite no dependence on the time, these guidance laws still involve each interceptor working to minimize its own unique parameter instead of a shared minimization goal.

Here we propose a cooperative guidance law that can lead to simultaneous interception of a target where interceptors work together to minimize shared parameters. The guidance law operates by having neighboring interceptors work together to minimize the time-to-go difference between them while still keeping on track to intercept the target. The guidance law is developed using sliding mode control with a multiple sliding surface approach, where each neighboring pair of interceptors has a sliding surface between them to minimize the time-to-go differences between them and the overall encounter has one sliding surface to guarantee interception of the target.

The rest of this paper is organized as follows: the mathematical model of the problem is presented in Sec. II. The principle behind the guidance law is discussed in Sec. III, followed by the derivation of said guidance law in Sec. IV. The performance of the guidance law is analyzed in Sec. V followed by concluding remarks in Sec. VI.

II. Problem Formulation and Nonlinear Kinematics

Consider the scenario of multiple interceptors pursuing a single target. Each interceptor has the objective of intercepting the target at the same time as the other interceptors, what will be referred to as simultaneous interception. The scenario is assumed to be a point-mass planar engagement with no effects due to gravity. Each interceptor is assumed to travel at a constant speed. The interceptors are assumed to have perfect information on the states of the other interceptor, as well as perfect information about the target. Collisions between the different pursuing interceptors are not taken into account.

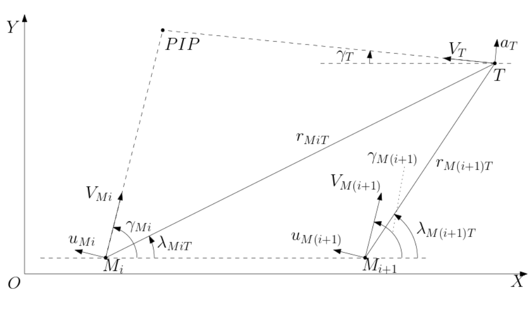

Fig. 1: Two-on-one engagement schematic

First the nonlinear equations of motion of the problem will be discussed. A schematic of a sample engagement with two interceptors can be seen in Fig. 1. Pictured also is the predicted interception point (PIP). For the sake of derivation, we will assume perfect knowledge of the problem and ideal dynamics. The kinematics of the engagement between each interceptor $i \in \{M_1, M_2\}$ and the target can be defined by:

$$\mathbf{x}_i = [r_{MiT} \;\; \lambda_{MiT} \;\; \gamma_{Mi}]^T \tag{1}$$

where r_{MiT} is the range from the interceptor to the target, λ_{MiT} is the line of sight (LOS) angle between the interceptor and the target, and γ_{Mi} is the interceptor's path angle. The equations of motion are given by:

$$\begin{cases} \dot{r}_{MiT} = -V_{C,MiT} \\ \dot{\lambda}_{MiT} = V_{\lambda,MiT}/r_{MiT} \\ \dot{\gamma}_{Mi} = u_{Mi}/V_{Mi} \end{cases} \tag{2}$$

where u_{Mi} is the acceleration command of the i-th interceptor and V_{Mi} is its speed. In addition, $V_{C,MiT}$ is the closing speed in the i-th engagement and is given by:

$$V_{C,MiT} = V_T \cos(\gamma_T + \lambda_{MiT}) + V_{Mi} \cos(\gamma_{Mi} - \lambda_{MiT}) \tag{3}$$

and the speed perpendicular to the $M_i - T$ LOS $V_{\lambda,MiT}$ is given by:

$$V_{\lambda,MiT} = V_T \sin(\gamma_T + \lambda_{MiT}) - V_{Mi} \sin(\gamma_{Mi} - \lambda_{MiT}) \tag{4}$$

where V_T is the speed of the target and γ_T is the target's path angle. The rate of change of γ_T is given by:

$$\dot{\gamma}_T = \frac{a_T}{V_T} \tag{5}$$

where a_T is the target's acceleration.

III. Guidance Principle

A. Definition of the Error

The goal of intercepting the target simultaneously can be broken down into two subgoals: intercepting the target and arriving at the same time. In order to achieve the second goal, each pair of neighboring interceptors work to minimize the time-to-go difference between them. This is done through the introduction of one error in the encounter for each neighbor pair defined as the time-to-go difference. Each interceptor is required only to share information with its immediate neighbors in order to minimzie this error. The error for each neighbor pair can be written as:

$$e_i = t_{go,MiT} - t_{go,M(i+1)T} \tag{6}$$

Next, the first goal must also be explicitly enforced due to the existence of scenarios where the time-to-go difference is minimized but the target is not intercepted, for example a case where the interceptors fly away from the target maintaining the same range. In order to remove this case, all that is needed is that one interceptor will be forced to intercept the target, as the other interceptors will work to match their time-to-go and therefore intercept the target as well. To this end, the final error is defined as the product of all the $\dot{\lambda}_{MiT}$ in the encounter, guaranteeing that at least one interceptor will have a $\dot{\lambda}$ of zero, or that some interceptors together will have a $\dot{\lambda}_{MiT}$ that is very small, effectively bringing the product to zero. This in effect enforces parallel navigation and works for interception. In order to implement this error, global information sharing is necessary so the interceptors can share their $\dot{\lambda}_{MiT}$ with each other. This error can be written as:

$$e_N = \prod_{i=1}^{N} \dot{\lambda}_{MiT} \tag{7}$$

B. Time-to-go Approximation Scheme

Considering the explicit use of time-to-go in the error scheme, of utmost importance is the choice of the approximation scheme to be used for the time-to-go. Here, an approximation of time-to-go will be used which includes a term accounting for the heading error σ_{Mi}, due to the large deviations from the LOS that are necessary in order to minimize the time-to-go differences. The time-to-go approximation for a stationary target and accounting for heading error is introduced in [1], and given by:

$$\bar{t}_{go,MiT} = \frac{r_{MiT}}{V_{Mi}} \left(\frac{\sigma_{Mi}^2}{2N' - 1} + 1 \right) \tag{8}$$

where $\sigma_{Mi} = \gamma_{Mi} - \lambda_{MiT}$ and N' represents the navigation gain in proportional navigation. $V_{C,MiT}$ is not used in this approximation because $V_{C,MiT}$ is not assumed to be constant. This approximation will be used in the derivation of the guidance law in the following section.

IV. Guidance Law Derivation

In order to implement the guidance law, the sliding mode control methodology is implemented. Sliding mode control is based on defining some "surface" in the encounter that must be equal to zero. Starting with the assumption that the surface is already equal to zero, the derivative of the surface is taken and set to zero to find the control that will keep the problem with the sliding surface equal to zero, known as the equivalent controller. Next, the original assumption is removed, and a constant addition is made to the equivalent controller with its sign based on the sign of the value of the sliding surface. This additional controller is known as the uncertainty controller and it works to bring the sliding surface to zero. Here multiple sliding surfaces will be used in order to derive the guidance law.

A. Equivalent Controller

Since the control command appears within the first derivative of both of the errors, the sliding surface can be taken to be the errors themselves. Using this, the guidance law will be derived using the sliding surface presented in Eq. 9.

$$\mathbf{s} = \begin{cases} s_1 = t_{go,M1T} - t_{go,M2T} \\ s_2 = t_{go,M2T} - t_{go,M3T} \\ \vdots \\ s_{N-1} = t_{go,M(N-1)T} - t_{go,MNT} \\ s_N = \prod_{i=1}^{N} \dot{\lambda}_{MiT} \end{cases} \tag{9}$$

Differentiating the sliding mode and moving it to matrix form, the equation can be written as:

$$\dot{\mathbf{s}} = \underbrace{\begin{bmatrix} \xi(1) & -\xi(2) & \dots & 0 \\ 0 & \xi(2) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & -\xi(N) \\ \zeta(1) & \zeta(2) & \dots & \zeta(N) \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} u_{M1} \\ u_{M2} \\ \vdots \\ u_{M(N-1)} \\ u_{MN} \end{bmatrix}}_{\mathbf{u}} + \underbrace{\begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_{N-1} \\ B \end{bmatrix}}_{\mathbf{g}} \tag{10}$$

where

$$A_i = \frac{r_{MiT}}{V_{Mi}} \left(\frac{\sigma_{Mi}^2}{2N' + 1} - \frac{2\sigma_{Mi}}{2N' - 1} \dot{\lambda}_{MiT} + 1 \right) - \frac{r_{M(i+1)T}}{V_{M(i+1)}} \left(\frac{\sigma_{M(i+1)}^2}{2N' + 1} - \frac{2\sigma_{M(i+1)}}{2N' - 1} \dot{\lambda}_{M(i+1)T} + 1 \right) \tag{11}$$

$$B = \sum_{i=1}^{N} \left(\prod_{j=1}^{N} (\dot{\lambda}_{MjT}) \frac{2V_{C,MiT}}{r_{MiT}} \right) \tag{12}$$

The help functions $\xi(i)$ and $\zeta(i)$ are defined by:

$$\xi(i) = \frac{r_{MiT}}{V_{Mi}^2} \frac{2\sigma_{Mi}}{2N' - 1} \tag{13}$$

$$\zeta(i) = -\prod_{\substack{j=1 \\ j \neq i}}^{N} (\dot{\lambda}_{MjT}) \frac{\cos(\gamma_{Mi} - \lambda_{MiT})}{r_{MiT}} \tag{14}$$

Setting $\dot{\mathbf{s}} = 0$ and solving for $\mathbf{u}$ gives the equivalent controllers for the interceptors in the absence of errors:

$$\mathbf{u}^{eq} = \begin{bmatrix} u_{M1}^{eq} \\ u_{M2}^{eq} \\ \vdots \\ u_{N-1}^{eq} \\ u_N^{eq} \end{bmatrix} = -\mathbf{H}^{-1}\mathbf{g} \tag{15}$$

B. Uncertainty Controller

The full controller, along with the uncertainty controller, is chosen to be:

$$\mathbf{u} = \mathbf{u}^{eq} - \mathbf{H}^{-1}\mathbf{M} sgn(\mathbf{s}) \tag{16}$$

where $\mathbf{M}$ is a control gain matrix given by

$$\mathbf{M} = \begin{bmatrix} \mu_1 & 0 & \dots & 0 & 0 \\ 0 & \mu_2 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \mu_{N-1} & 0 \\ 0 & 0 & \dots & 0 & \mu_N \end{bmatrix} \tag{17}$$

where μ_i are the control gains chosen for each sliding surface and

$$sgn(\mathbf{s}) = \begin{bmatrix} sign(s_1) \\ sign(s_2) \\ \vdots \\ sign(s_{N-1}) \\ sign(s_N) \end{bmatrix} \tag{18}$$

In addition, a boundary layer is applied to the problem to reduce chattering. Under a certain value of s_i, which we refer to as $s_{bound,i}$, the acceleration command becomes:

$$\mathbf{u} = \mathbf{u}^{eq} - \mathbf{H}^{-1}\mathbf{M}\mathbf{s} \tag{19}$$

and different values of μ_i are used to compose $\mathbf{M}$. Finally, due to the divergence of $\dot{\lambda}_{MiT}$ towards the end of the encounter, a switch to PN is used in the final stages to guarantee interception. This switch will be further explored in the Sec. V.

V. Performance Analysis

In this section performance of the guidance law is analyzed using numerical simulation with the nonlinear kinematics present in Eq. 2. In addition, the dynamics of the interceptors are assumed to be first order in order to show the robustness of the guidance law and a maximum acceleration is introduced to bring realism to the simulation. First, a test scenario for two interceptors and a stationary target will be outlined and presented. Next, results will be compared for different values N' in the t_{go} approximation scheme. Then, a test run will be performed for the case of more than two interceptors. Finally, a test run will be performed for the case of a target with constant velocity using a predicted interception point. The ode45 solver is used in MATLAB in order to run the simulations.

For all tests cases, the time constant for both interceptors is $\tau_M = 0.1$ and the sliding mode constants are set as $\mu_1 = 100$ and $\mu_2 = 10$ with the boundary layers set as $s_{bound,1} = 1[m]$ and $s_{bound,2} = 1[rad/s]$, the alternative value of μ being $\mu_{bound} = 1$. These gains are chosen manually through trial and error. In addition, $N' = 7$ is used for the time to go approximation and a switch to PN is applied at $500[m]$ from the target with $N' = 3$.

A. Sample Run

For the initial test scenario, the interceptor speed is assumed to be $V_{Mi} = 380[m/s]$ and the maximum acceleration is defined as $a_{Mi}^{max} = 30[g]$. The first interceptor starts at initial position $[-3000[m], 3000[m]]$ and the second interceptor starts at initial position $[-2500[m], 2000[m]]$, with both interceptors heading directly towards the target which sits at $[0[m], 0[m]]$ in the beginning. The simulation of the test case can be seen in Figs. 2-5.

Fig. 2 shows the trajectories of the simulation run. The interceptor that is farther away heads straight to the target while the other interceptor adjusts its trajectory to bring itself to intercept the target simultaneously with the other interceptor. This fits with the original goals that were outline

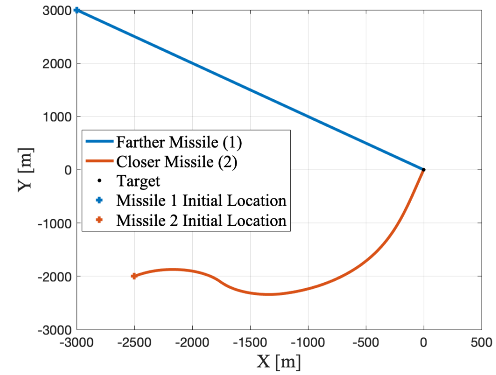

Fig. 2: Trajectories for a two interceptor sample run

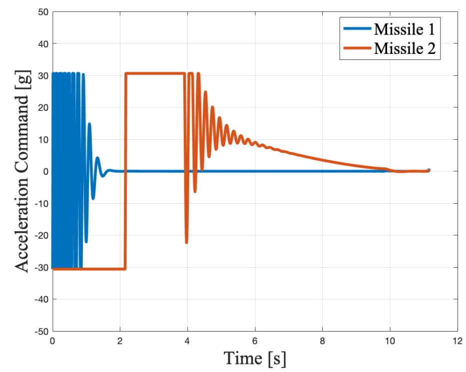

Fig. 3: Acceleration command for a two interceptor sample run

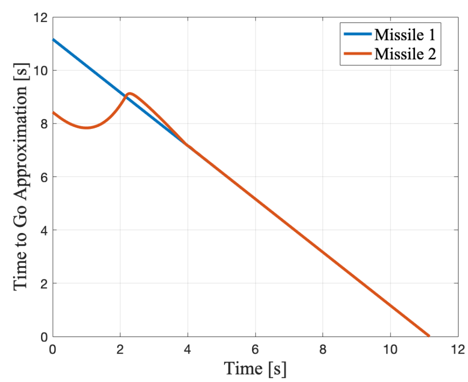

Fig. 4: Time-to-go approximations for a two interceptor sample run

for the guidance law. The acceleration command throughout the encounter is shown in Fig. 3. The most noticeable aspect of the acceleration commands is the chattering, which can lead to implementation problems. There are several methods for the removal of chattering that are known in the literature, and for the sake of simplicity they are not implemented here. It can also be seen that there is an initial adjustment period for interceptor 2, which brings it to match the time-to-go of interceptor 1, and then its acceleration command decreases

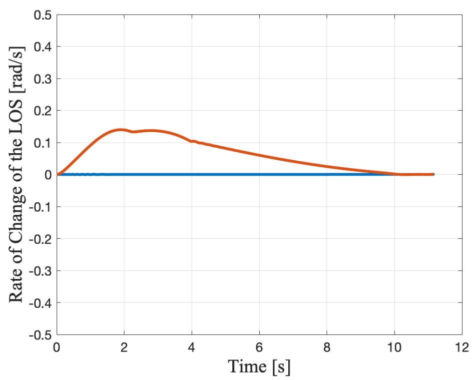

Fig. 5: $\dot{\lambda}_{MiT}$ for a two interceptor sample run

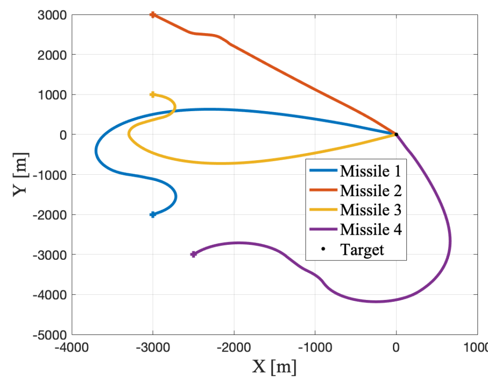

Fig. 6: Trajectories for a four interceptor sample run

until the interception. This can also be seen for interceptor 1, which after an initial chattering phase has an acceleration command of zero throughout the entire encounter. While not shown here, the boundary layer greatly reduces the chattering shown by the acceleration command.

Looking at Fig. 4, it can be seen that the guidance law successfully changes the time-to-go and increases the time-to-go of interceptor 2 until it matches that of interceptor 1. In addition, it does this quite fast, reaching similar time-to-go as interceptor 1 within 3 seconds of the encounter. The guidance law also deals well with the small overshoot that arises as a result of changing the time-to-go, and manages not only to increase the time-to-go of interceptor 2, but also to decrease it. Most of the initial time-to-go shift is done by matching the ranges of the two interceptors, and overshoot is handled with by decreasing the heading error of interceptor 2. The rate of change of the LOS angle for each interceptor is shown in Fig. 5. It can be seen that $\dot{\lambda}_{M1T}$ stays at zero throughout the entire encounter, effectively enforcing PN on interceptor 1. It can also be seen that $\dot{\lambda}_{M2T}$ is not zero for most of the encounter, rather has a positive value during the period of matching time-to-gos and then slowly declines back to zero. Without the switch to PN at the end of the encounter, $\dot{\lambda}_{M2T}$ would diverge at the very end of the encounter, leading to miss distance for interceptor 2.

B. Multiple interceptor Test Run

To test the robustness of the guidance law, a sample run was run for four interceptors with four different speeds. interceptor 1 has an initial condition of $[-3000, 2000]$ with a speed of $V_{M1} = 380[m/s]$, interceptor 2 has an initial condition of $[-3000, 3000]$ with a speed of $V_{M2} = 250[m/s]$, interceptor 3 has an initial condition of $[-3000, 1000]$ with a speed of $V_{M3} = 300[m/s]$, and interceptor 4 has an initial condition of $[-2500, -3000]$ with a speed of $V_{M4} = 450[m/s]$. The results can be seen in Figs. 6-9.

The trajectories for the sample run with four interceptors can be seen in Fig. 6, where the four interceptors are able to all intercept the target at the same time. Even when not strictly ranked, the guidance law automatically chooses the interceptor with the largest time-to-go to head straight to the target ($\dot{\lambda}_{MiT} = 0$). This includes taking into account the difference in the velocities between the four interceptors, which the guidance law is successfully able to account for and still cause simultaneous interception. This allows the guidance law to have flexibility on the structure of the sliding surface matrix. The time-to-go approximations for the four interceptors can be seen in Fig. 7. Even with the addition of two more interceptors, the guidance law is still able to converge all four interceptors to similar time-to-gos within a

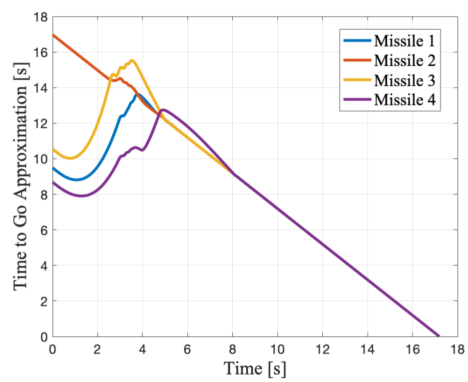

Fig. 7: Time-to-go approximations for a four interceptor sample run

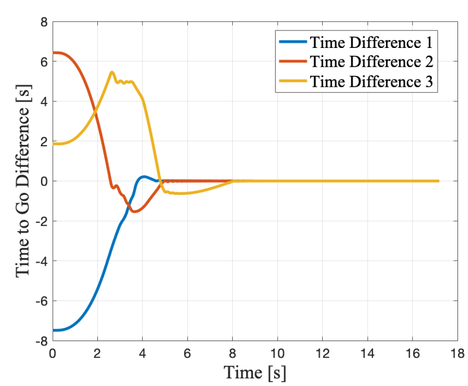

Fig. 8: Time-to-go differences for a four interceptor sample run

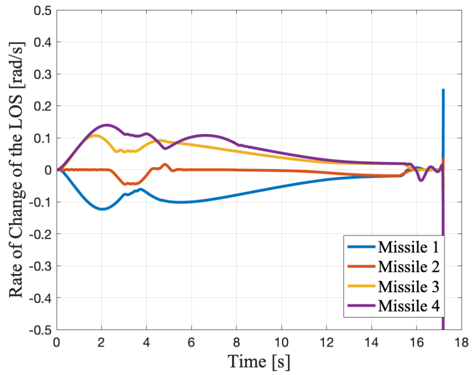

Fig. 9: $\dot{\lambda}_{MiT}$ for a four interceptor sample run

short time frame, of about $3[s]$.

The time-to-go approximation differences (the errors) can be seen in Fig. 8. Here it can be seen that the guidance law works just as well for a negative time-to-go difference as for a positive one. This, together with the above conclusion about the selection of the largest time-to-go, means that the guidance law does not require any calculations or knowledge about the encounter before launching the interceptors, but instead will organize the interceptors on the fly. The rate of change of the LOS for the interceptors can be seen in Fig. 9. It can be seen that all of the interceptors keep a $\dot{\lambda}$ that is relatively small throughout the encounter. This means that towards the end of the encounter no interceptor is heading straight to the target exactly, but rather the multiplication of all the $\dot{\lambda}$'s leads to the final error being close to zero.

Important to note here is that running this simulation without the switch to PN still results in a successful interception of the target by all four interceptors (even though the case presented here does use a switch for the sake of consistency). The factors that cause this success are still under investigation - it may have to do the combination of low $\dot{\lambda}$ instead of one interceptor having a $\dot{\lambda}$ of zero.

VI. Conclusions

It was shown here that sliding surfaces based on the time-to-go differences between neighboring interceptors create a robust guidance law that leads to simultaneous interception. The guidance law does not require any precalculation or ordering of the interceptors based on their distance from the target or the time-to-go, and instead will automatically organize the interceptors during the encounter. It was also shown that a guidance law can be developed using a multiple sliding surface framework without a predefined number of sliding surfaces, rather a derived framework that can be extended to the number of desired interceptors.

While it works well, the developed guidance law is not optimized and the interceptors continue to maneuver throughout the encounter. Further research might be done into optimizing the developed guidance law so that the interceptors do not have to accelerate all the time and to save control effort. In addition, different PIP approximation schemes can be applied to the guidance law in order to extend it to cases with a moving or maneuvering target as well.

Acknowledgement

This research was supported in part by the Israel Science Foundation (grant no. 1459/21).

References

[1] I. S. Jeon, J. I. Lee, and M. J. Tahk, "Impact-time-control guidance law for anti-ship missiles," *IEEE Transactions on Control Systems Technology*, vol. 14, no. 2, pp. 260–266, 2006.

[2] S. R. Kumar and D. Ghose, "Sliding mode control based guidance law with impact time constraints," in *2013 American Control Conference*, 2013, pp. 5760–5765.

[3] D. Cho, H. J. Kim, and M. J. Tahk, "Nonsingular sliding mode guidance for impact time control," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 1, pp. 61–68, 2016. [Online]. Available: https://doi.org/10.2514/1.G001167

[4] A. Saleem and A. Ratnoo, "Lyapunov-based guidance law for impact time control and simultaneous arrival," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 1, pp. 164–173, 2016. [Online]. Available: https://doi.org/10.2514/1.G001349

[5] ——, "Two stage proportional navigation guidance law for impact time control," in *2018 Indian Control Conference (ICC)*, 2018, pp. 312–317.

[6] ——, "Lyapunov-based guidance law for impact time control and simultaneous arrival," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 1, pp. 164–173, 2016. [Online]. Available: https://doi.org/10.2514/1.G001349

[7] S. R. Kumar and D. Ghose, "Impact time and angle control guidance," in *AIAA Guidance, Navigation, and Control Conference*. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2015-0616

[8] ——, "Sliding mode control based guidance law with impact time constraints," in *2013 American Control Conference*, 2013, pp. 5760–5765.

[9] A. Sinha and S. R. Kumar, "Supertwisting control-based cooperative salvo guidance using leader–follower approach," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 5, pp. 3556–3565, 2020.

[10] I. S. Jeon, J. I. Lee, and M. J. Tahk, "Homing guidance law for cooperative attack of multiple missiles," *Journal of Guidance, Control, and Dynamics*, vol. 33, no. 1, pp. 275–280, 2010. [Online]. Available: https://doi.org/10.2514/1.40136

[11] J. Zhou and J. Yang, "Distributed guidance law design for cooperative simultaneous attacks with multiple missiles," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 10, pp. 2439–2447, 2016. [Online]. Available: https://doi.org/10.2514/1.G001609

[12] S. Zhang, Y. Guo, Z. Liu, S. Wang, and X. Hu, "Finite-time cooperative guidance strategy for impact angle and time control," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 57, no. 2, pp. 806–819, 2021.

[13] Q. Zhao, X. Dong, X. Song, and Z. Ren, "Cooperative time-varying formation guidance for leader-following missiles to intercept a maneuvering target with switching topologies," *Nonlinear Dynamics*, vol. 95, no. 1, pp. 129–141, 2019. [Online]. Available: https://doi.org/10.1007/s11071-018-4555-9

[14] R. V. Nanavati, S. R. Kumar, and A. Maity, "Nonlinear simultaneous interception guidance strategies for stationary targets," *Journal of Guidance, Control, and Dynamics*, vol. 43, no. 1, pp. 154–161, 2020. [Online]. Available: https://doi.org/10.2514/1.G004424

[15] B. Zadka, T. Tripathy, R. Tsalik, and T. Shima, "Consensus-based cooperative geometrical rules for simultaneous target interception," *Journal of Guidance, Control, and Dynamics*, vol. 43, no. 12, pp. 2425–2432, 2020. [Online]. Available: https://doi.org/10.2514/1.G005065

[16] S. He, W. Wang, D. Lin, and H. Lei, "Consensus-based two-stage salvo attack guidance," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 3, pp. 1555–1566, 2018.