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ADAPTIVE ELECTROSTATIC FORCE ALGORITHM FOR MULTIPLE INVADER DRONES' ATTACKING MANEUVER

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Abstract. *We propose an attacking maneuver strategy of multiple invader drones to strike an area guarded by multiple defender drones. This paper's problem domain is related to the "Multiple Invader Drones vs. Multiple Defender Drones" battle strategy. Here, we develop an optimization algorithm conducted by multiple invader drones to maximize the damage received by an area guarded by multiple defender drones. We adopt the Electrostatic Force Law principle as our algorithm basis, where we represent each drone as a charged particle. After testing our proposed method in a dynamic 3D simulation environment, we confirm that our proposed method experimentally performs well.*

Keywords: Attack maneuver, Battle strategy, Electrostatic force law, Multiple drones, Performance evaluation

1. Introduction.

The usage of autonomous drones for military battles has become an interesting topic nowadays. Because drone technology development is relatively rapid, using autonomous drones in a military battle has many benefits. Fewer casualties and more efficiency are some of the benefits of using autonomous drones in a military battle. We have explored their usage and developed some autonomous drone defense coordination algorithms in [1,2] to maximize their potential in a military battle. In [1,2], we designed some effective maneuver strategies among a group of defender drones to defend an area from an attack of multiple invader drones. We concluded that a group of autonomous defender drones could minimize damage produced by multiple attacker drones by establishing a good coordination algorithm.

Besides defending an area, sometimes a group of drones is used to invade an area effectively. A military army might use drones to invade/attack a villain's headquarter. In this case, manual control of drones using some remote control might be helpful. However, the small available number of pilots controlling the drones may limit this approach's

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effectiveness. Thus, we analyze that autonomous, multiple invader drones can be a good alternative.

There is some research related to drone combat maneuvers, for example, [3-5]. Research on [6-8] also studies the potential usage of drones in warfare. Although multiple invader drones have good potential for invading maneuvers toward targets, they require an effective autonomous coordination algorithm and communication architecture to conduct an excellent maneuver. Take a look at the research example provided in [9-19]. All the research indicates that a drone swarm requires sophisticated algorithms or movement strategies to perform a good maneuver. Nevertheless, this kind of coordination algorithm has one common potential drawback: it requires extra time and computation to communicate before performing any movement. This requirement might be dangerous in a highly dynamic environment such as a military battle because it delays invader drone movements. In any research related to attack strategy, execution time is always essential, as also stated in [20].

In this paper, we develop an invading maneuver algorithm performed by a group of invader drones without communicating with each other. We use the adaptive electrostatic force law approach as our basis. In our proposed method, each invader drone can limitedly detect the position of defender drones around it. Each invader drone calculates the best movement it should take in a specific situation. The best part of the proposed algorithm is that although there is no communication among the invader drones, each invader may establish a well-organized movement that can invade an area through the area's weak defense point. Thus, the damage produced is relatively high. To help readers comprehensively understand our study, we organize our paper as follows. In Section 2, we describe the research scope of this paper. Then, in Section 3, we explain our proposed method, while the experiment results and their analysis are provided in Section 4 and Section 5. Finally, in Section 6, we emphasize the conclusion of our work.

2. **Research Scope.** We test our proposed method in a 3D simulation environment. In this research, we develop an invading maneuver algorithm performed by a group of invader drones when striking an area. In our simulation, the area is protected by some autonomous defender drones. Thus, our research's problem domain is the "Multiple Invader Drones vs. Multiple Defender Drones" combat strategy. From a computer science perspective, our research's problem domain is related to the pursuit-evasion problem variant. Here, the pursued agents have a mission to create as much damage as possible toward a single target. Some researchers call this topic Unmanned Combat Aerial Vehicle (UCAV) research field. Our research scope is similar to [21], where we develop an algorithm to solve a specific problem.

Figure 1 shows the problem domain of our research. In Figure 1, a group of autonomous invader drones tries to strike an area guarded by a group of autonomous defender drones. There are many research types related to this topic, for example, [22-25]. In the process, the invader drones cannot hit/strike any defender drones. The invader drones can only produce damage to a target area. The closer an invader drone is to its target, the more significant damage it creates. Thus, to cause more substantial damage to its target, the invader drones should have a good movement algorithm to avoid defender drones while diligently getting closer to their target.

Please note that the term "invader" drones and "defender" drones may vary in many research articles. Invader drones sometimes are called attacker drones because they try to attack an area. Meanwhile, defender drones are sometimes called pursuer drones because they try to pursue and immobilize invader drones. For simplicity, in this article, we call

FIGURE 1. Research problem domain illustration

the attacker drones group Multiple Invader Drones (MIDs), and we call the defender drones group Multiple Defender Drones (MDDs).

To scientifically measure our proposed algorithm's effectiveness, we configure all MIDs and MDDs to have the same speed and detection range capabilities in our research. Figure 2 shows the region variety of a defender drone. A defender drone can detect any invader drone's existence if the invader drone is located inside the defender drone's R2 range. If any invader drone is located in the R3 range, the invader drone cannot be detected by the defender drone. R1 in Figure 2 indicates the shooting range of a defender drone. If any invader drone is located in the R1 range, the invader drone is automatically demolished in the experiment. We do not describe the technical aspect of how a defender drone shoots an invader drone because this action's physical implementation depends on the defender drone's hardware specification. Many researchers have also made the same approach [1,2]. We refer to [2] for the target area damage equation and any drone configuration we use in this research. This paper focuses on developing an effective MIDs' invading maneuver algorithm.

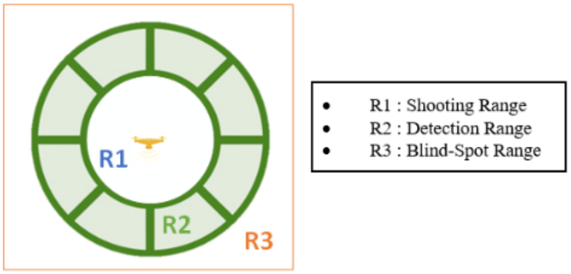


FIGURE 2. Region variety of a defender drone

Slightly different from the defender drone region variety, an invader drone does not have an R1 region to shoot any defender drone. An invader drone can only produce damage to a target area. The longer an invader is closer to a target area, the greater its damage to the area. Although all drones have a limited R2 range, all the drones know exactly the target area's position. Because every drone has a good detection range, any two different drones from the same team will not collide with each other. In our experiment, every drone has a collision-avoidance sensor and algorithm that makes two different drones tend to bump into each other when their distance is relatively close. Please note that we do not describe the MDDs and MIDs weapon's technical issue because it has been described in [2]. We do not explain either what kind of sensor any drone has or what path-planning and obstacle-avoidance algorithm each drone uses. Many research types have been done related to them; for example, [7,26-32]. We only focus our explanation on the MIDs invading maneuver. In our study, the more significant damage produced by the MIDs, the better the invading algorithm is.

3. **Proposed Method.** In our proposed method, we treat every defender drone and a target area as charged particles. We treat a defender drone as a positively charged particle while the target area as a negatively charged particle. In this research, an invader drone acts as a positively charged particle. We use Electrostatic Force (El-Force) Law/Coulomb's Law as our basis. The formula of El-Force Law is written in (1), where F is the El-Force, k is a constant value, q_1 is the charged value of particle 1, q_2 is the charged value of particle 2, and r is the distance between particle 1 and particle 2. Please notice that q_1 and q_2 may be positive or negative according to their charged characteristic. If the result of (1) is positive, then the El-Force between two charged particles is repulsive; meanwhile, if the result of (1) is negative, then the El-Force between two charged particles is attractive.

$$F = \frac{k \cdot q_1 \cdot q_2}{r^2} \tag{1}$$

$$F_{Movement} = \sum_{i=1}^{n} \frac{k \cdot q_{invader} \cdot q_i}{r^2} \tag{2}$$

In our proposed algorithm, particle 1 represents an invader drone; particle 2 represents a defender drone or a target area. Accordingly, an invader drone movement in any situation is calculated according to (2), where particle-i is the target area or defender drones around an invader drone. Please notice that we conduct our experiment in a 3D environment; thus, the value of (2) is calculated in a 3D space. Figure 3 illustrates how our algorithm works. In any situation, an invader drone moves according to the sum of El-Force towards it. Because the El-Force is a vector value, we could easily use the vector summation rule to calculate the El-Force result felt by an invader drone. As illustrated in Figure 3, suppose an invader in Figure 3 detects two defender drones' existence around it. According to (2), the invader drone calculates the El-Force resultant it feels. In Figure 3, the target

FIGURE 3. Proposed method illustration (2D visualization for the 3D environment used in our experiment)

and the defenders are located on the invader's right and downside, respectively. Thus, the force resultant is at the invader upside (for illustration simplicity). Please note that two invaders do not affect each other's movements in our proposed algorithm, so we do not consider the other invader charge as our consideration in (2).

In our proposed method, the effective attacking maneuver can be produced without coordination among MIDs because any MDDs formation can make different invader drone movements. It can happen because (2) is significantly influenced by invader drones' position. Take a look at Figure 4 as an example. In Figure 4, two different invader drones (invader1 and invader2) might detect the same situation. However, because the positions of invader1 and invader2 are different, their response to the same situation may also differ. In the long run, the MIDs can produce an effective movement that can exploit the weak point of MDDs' defense.

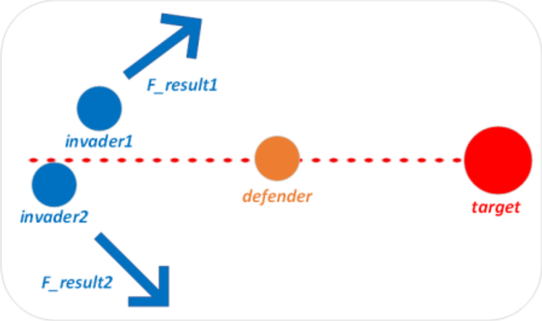


FIGURE 4. Illustration of how MIDs construct effective movement

Theoretically, our proposed method can effectively avoid any defender drone because whenever any defender drone comes closer to an invader drone, the repulsive El-Force produced becomes higher. Consequently, the invader drone tends to have a bigger repulsive force. In other words, the tendency of an invader drone to avoid a defender drone will increase whenever the defender drone gets closer to the invader drone. Although this approach has its own advantage, this approach has a drawback: The invader drone tends to avoid MDDs without producing damage to a target area. In our proposed method, we develop an adaptive El-Force approach to overcome this drawback, where the charge of the target area gradually increases over time.

In our proposed algorithm, at the beginning of the iteration, the target area and MDDs have an equal charge (MDD: positive charge, target area: negative charge). Suppose that the charge of every defender drone in the initial state is $+c$, then the target area charge in the initial state is $-c$. Our proposed algorithm's adaptive part occurs when an invader drone cannot produce any damage to a target for a specific iteration time (we call it $increment\_time\_limit$). If it happens, then the target area's charge will increase by the amount of its charge in the initial state. As a result, an invader drone's attractive force to a target area will increase over time. Eventually, the invader drone will tend to move to its target regardless of surrounding MDDs. We call it a kamikaze maneuver. It happens when an invader drone prefers to conduct a suicide maneuver instead of a "forever run away" maneuver. Algorithm 1 shows our method workflow.

Please note that Algorithm 1 is called in each iteration. Thus, the procedure is called inside the looping process of our simulation. In our proposed method, Algorithm 1, Line 03 is the core process that performs every invader drone movement. Because Line 03 states

Algorithm 1. Proposed adaptive El-Force algorithm

```
01: procedure Adaptive Electrostatic Force Movement
02:     calculate electrostatic force resultant
03:     move along El-Force resultant direction with own speed
04:     if cannot attack the target for increment_time_limit then
05:         increase target area charge by its initial charge value
06:     endif
07: end procedure
```

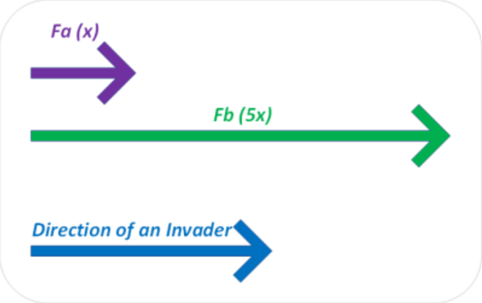


FIGURE 5. Illustration of how different values of force resultant may produce the same movement if their vector-directions are the same

that any invader drone should move along the El-Force resultant direction with its own speed, the El-Force resultant's exact value is not important. Please notice that speed is different from velocity. Speed is a scalar value; meanwhile, velocity is a vector value. For simplicity, we can describe velocity as a speed with a direction. Thus, Algorithm 1, Line 03, describes that an invader drone should move with its speed with the direction to be set equal to the vector direction of El-Force. In other words, the El-Force resultant direction is an invader drone's most crucial aspect to know to perform a movement. Figure 5 shows the illustration for this situation.

In Figure 5, El-Force F_a and F_b's values are different; however, their vector direction is equal. Assume that the value of F_a is x and the value of F_b is $5x$. Although both El-Forces have different values, both El-Forces have the same vector direction. Consequently, any invader drone with El-Force resultant F_a or F_b will produce the same movement because the movement of an invader drone is related to the vector direction of an El-Force. Accordingly, the exact value of k and $q_{invader}$ in (2) can be ignored because they only affect the value of El-Force without changing the El-Force resultant vector direction. Consequently, we can assume the value of both variables (k and $q_{invader}$) as 1 without affecting MIDs' movement direction.

The exact value of $q_{defender}$ is not so significant either. What truly important is its ratio towards q_{target_area}. In our proposed method, we can assume the charge value of $q_{defender}$ as $+c$ and q_{target_area} as $-c$ in the initial state. Whenever an invader drone cannot attack a target area for *adaptive_time_limit* period, the charge value of q_{target_area} will change to $-2c$, $-3c$, $-4c$, $\ldots$, and so on. We configure the increment value to be constant to keep an invader drone's changing behavior stable. By doing so, we can clearly observe the effect of this value change on MIDs' behavior. The value of c can be any arbitrary number. The same approach also works for the r value of (2). The exact value of r is not so important. We can calculate r in meters, pixels, or any other distance unit. In our proposed method, we define our own distance unit to reduce computational complexity.

As described earlier, we configure the initial value of $q_{defender}$ and q_{target_area} as $+c$ and $-c$, respectively. Technically speaking, both values might be set not equal. However, we configure both values to be equal in the initial set to allow the MIDs to totally explore any possible weakness in MDDs formation. As you may observe, when both values are equal, an invader drone tends to avoid any defender drone in the beginning. We analyze that this approach may produce a good exploration result. As time goes by, the value of q_{target_area} will change, so an invader drone has a bigger tendency to move to its target. Consequently, the MIDs general movement will focus on exploiting a possible weakness in MDDs formation. This approach is one of the uniqueness of our proposed method.

The incremental contributions of the proposed method are described as follows.

1) It provides an efficient coordination algorithm for MIDs without requiring each drone in MIDs to communicate explicitly with each other. Thus, the execution time to coordinate is relatively fast.
2) It can adaptively adjust each drone movement in MIDs according to the change in environment.
3) To the best of the authors' knowledge, no research explicitly studies the drone swarm movement in military combat as an attacking troop. Thus, this study brings a novelty related to drone swarm movement strategy in the military.

4. **Experiment Results.** We have tested our proposed method in a 3D simulation environment built with Unity. In our experiment, we run multiple experiments for any configuration to measure the average damage value produced by MIDs toward a target area. The equation used to calculate this value refers to [2]. In short, the damage result indicates how great MIDs produce damage toward a target area. The bigger its value, the better the MIDs invading strategy. Theoretically, we can also measure how much time the MIDs need to perform an invading maneuver. However, because this paper focuses on producing a highly effective invading strategy, we focus our measurement solely on the damage result value.

Figure 6 illustrates how our 3D environment looks. In our environment, there is a mini-map in the top-right corner of our environment. This mini-map indicates a radar-like view

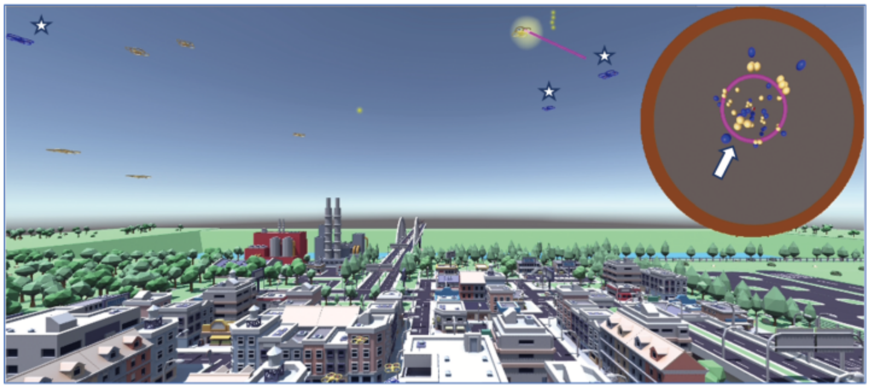


FIGURE 6. (color online) Simulation environment interface*

*Special Note: For readers who read this paper in black and white color format, please use this information. The drone with an additional star mark is originally printed in blue color. The other drones are printed in yellow color. The arrow on the top-right mini-map points to a pink circle that indicates the damaged border of CoG.

of our environment. Please notice that this mini-map is only for visualization/observation. Each drone has only a limited detection range, as described earlier. In our environment, brown drones represent MDDs; meanwhile, blue drones represent MIDs. The pink line in Figure 6 animates a defender drone's shooting action toward an invader drone, where the yellow sparkles are used to animate the vanished process of a shot invader drone. In our mini-map, the pink circle represents the area being guarded by MDDs.

Figure 7 shows the example formation of MIDs in the experiment. In our experiment, MIDs come from various direction. The number of MDDs and MIDs involved in our experiment is set to be various. Table 1 shows our experiment results. In Table 1, we use a varied number of MDDs and MIDs to measure our proposed method's effectiveness. Each damage value written in Table 1 is obtained from rounding the average value of the same amount of MDDs and MIDs experiment, repeated 10 times. Our experiment compares our proposed method with the Straight Forward (SF) MIDs attacking maneuver defined in [2]. We evaluate our proposed method's effectiveness against 4 different kinds of MDDs algorithms defined in [2]. Please note that we use [2] as our benchmark; thus, all detailed configurations used in our experiment refer to the configuration described in [2].

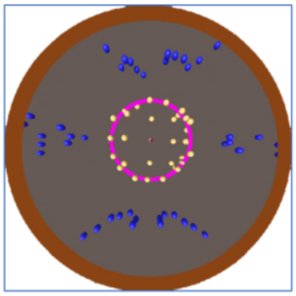


FIGURE 7. (color online) Example of MIDs formation when invading an area

TABLE 1. Experiment results for performance evaluation

No	**Amount**		**WD**		**BruteF**		**SwitchT**		**SSO65**	
	I	**D**	**SF**	**EF**	**SF**	**EF**	**SF**	**EF**	**SF**	**EF**
1	4	4	662	0	45	161	14	83	24	87
2	8	8	9	1034	9	11196	7	3342	29	4974
3	16	16	37	2957	5	5374	8	583	37	2149
4	32	32	36	6519	13	2983	3	361	2	251
5	64	64	0	1175	5	1418	19	339	1	179
6	128	64	11	6389	20	5977	14	2478	6	3249
7	256	64	14	6645	224	15585	33	16662	25	15300
8	32	64	0	2	0	68	0	147	0	17
9	16	64	0	1	0	37	4	36	0	8
10	16	32	5	3	1	155	4	123	2	29

Abbreviation: No = Case Number, I = Invader (MID), D = Defender (MDD), WD = Waiting Defender Algorithm Performed by MDD, BruteF = Brute Force Algorithm Performed by MDD, SwitchT = Switching Target Communication Strategy Performed by MDD, SSO65 = Social Spider Optimization Algorithm Performed by MDD with 65% Female Spider, SF = Straight Forward MID Attacking Algorithm Performance (Damage Produced), EF = Proposed Electrostatic Force Algorithm Performance (Damage Produced).

To analyze Table 1 data, firstly, we need to observe the MIDs and MDDs amount configuration, as shown in the gray area of Table 1 (first three columns). In the first 5 cases of Table 1, we set the proportion of MIDs and MDDs equal; however, the exact number of MIDs and MDDs involved increases in each case number. We set this configuration to understand whether the precise number of MIDs and MDDs involved matters affecting the damage produced by MIDs; otherwise, only the proportion matters. In experiments 6 and 7, we set the amount of MIDs to be much more than the amount of MDDs. We need to know whether the proposed method works better if the MIDs amount surpasses MDDs. Last, we set the amount of MIDs to be less than the amount of MDDs. We need to analyze whether our proposed method may keep producing good damage when the MIDs number is lower than the number of MDDs.

The main important data of our experiment lie in the white area of Table 1. The white area shows the damage produced by MIDs toward an area guarded by MDDs. The damage is calculated using the damage equation provided in [2]. The exact values in the white area might be different if we use any different damage equation or drone configuration, such as drone speed. However, the most important thing we need to highlight is our proposed improvement method compared to the SF method. For example, take a look at case number 7, experiment WD. As a result, SF produces 14 damage; meanwhile, our proposed method produces 6645 damage. This result indicates that our proposed method may produce $6645/14 \approx 475$ times more damage. In other words, we can declare that our proposed method may have a good performance when it produces a high damage value. While being compared to any method, our proposed method generally produces a higher damage value. This comparison approach has also been used in some research [1,2].

According to our experiment, we can conclude that the robustness of our proposed method has been tested well. According to Table 1, there are 10 cases where we test our proposed method's performance. In each case, we configure scenarios to compare our proposed method with SF method against 4 different MDDs algorithms, where we repeat the experiment 10 times for each scenario to calculate the average result. In other words, data in Table 1 is gathered after conducting 10 cases × 2 MIDs algorithms × 4 MDDs algorithms × 10 repetitions = 800 experiments. Please also note that in all those cases, we have tested experiments where the number of invader drones is greater than, equal to, and less than the number of defender drones. It indicates that we have configured the experiment to represent the varied possible situations. Besides, in all cases, the proposed method generally increases the damage caused by MIDs. Thus, we can analyze that our proposed method is practically robust to improve MIDs performance.

5. **Experiment Analysis.** Our proposed method can generally increase the damage produced by MIDs toward a target area. According to Table 1, our proposed method exceeds the performance of the Straight Forward MIDs invading maneuver strategy. Moreover, the increase of our proposed method is significantly bigger than the compared method. Figure 8 to Figure 11 show the significant differences in our proposed method performance compared to the Straight-Forward invading maneuver strategy. Those figures indeed represent the same data as Table 1, but with visualization.

According to our experiment, the exact number of MIDs and MDDs involved affects MIDs' damage more than the proportion of MIDs and MDDs. Please take a look at Table 1, cases 1-5. Although the proportion of MIDs and MDDs is set to equal $1:1$, when the number of MDDs increases, MIDs' damage tends to decrease. According to [1], it may happen because the MDDs may work better when their amount increases. When the number of MIDs exceeds the number of MDDs (case numbers 6 and 7), the damage produced significantly increases. It indicates that the more MIDs involved in the battle,

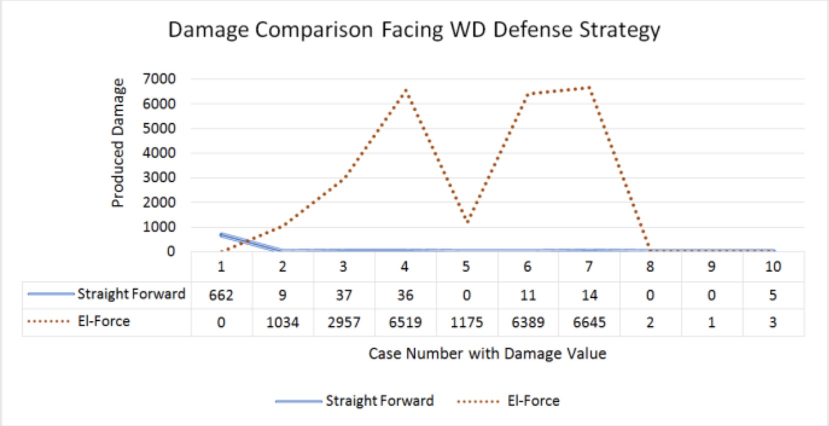


FIGURE 8. Performance result when facing WD

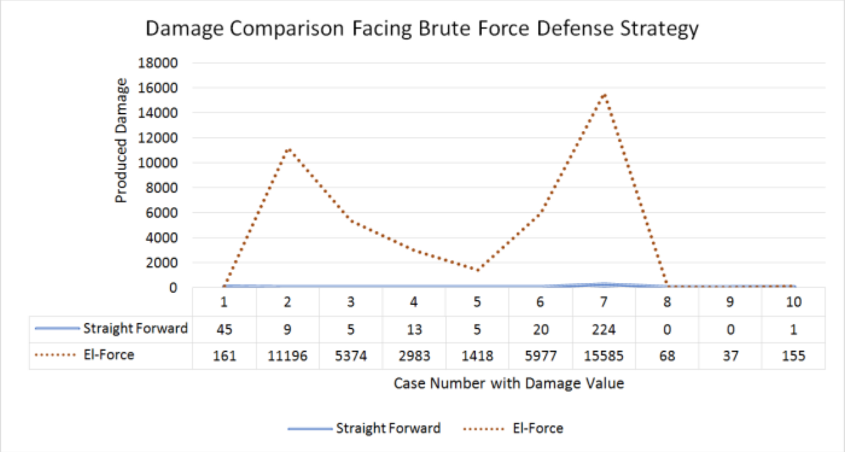
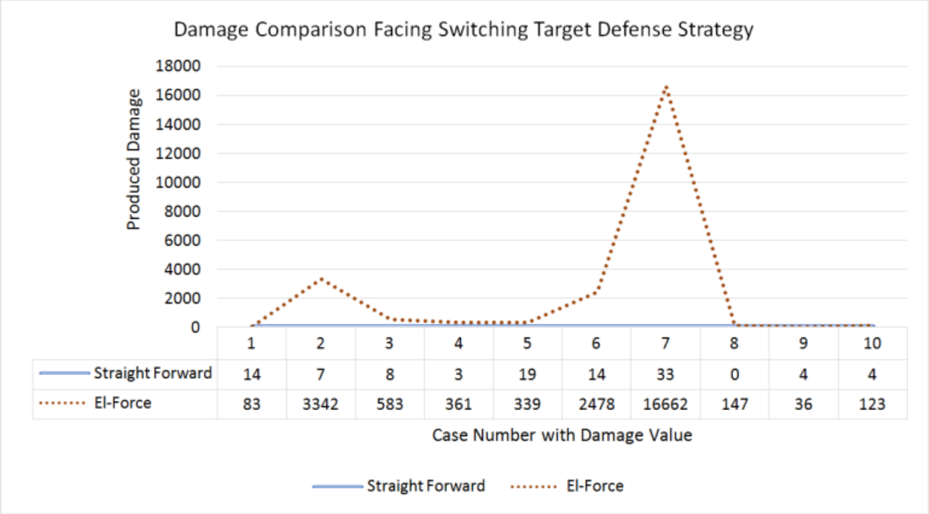


FIGURE 9. Performance result when facing brute force

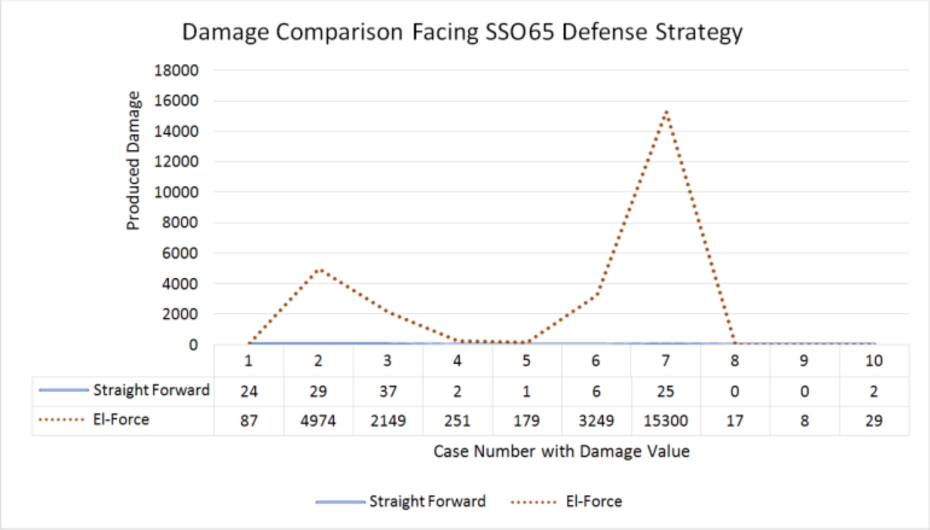
the more damage they may produce. Last, from experiment case numbers 8-10, we may conclude that damage produced by MIDs will decrease significantly when their number is much less than the number of MDDs. Take a look at case numbers 5 and 8. In cases 5 and 8, the damage of our proposed method against WD drops from 1175 to 2. It indicates that when the number of MIDs is lower than the number of MDDs, the MIDs performance drops significantly. Nevertheless, although our proposed method's performance decreases in case numbers 8-10, our proposed method performance still exceeds 100; which still outperforms the performance of SF in case numbers 8-10, where the damage produced by SF is not more than 5.

Based on our experiment, we can analyze that our proposed method performs well in various situations, even when the number of MIDs is lower than the number of MDDs. Our proposed method's primary benefit lies in its capability to find the weak point of MDDs maneuver without the need for MIDs to communicate with each other. As Figure 4 shows, whenever two different invader drones detect a defender drone, both invader's



	1	2	3	4	5	6	7	8	9	10
Straight Forward	14	7	8	3	19	14	33	0	4	4
El-Force	83	3342	583	361	339	2478	16662	147	36	123

FIGURE 10. Performance result when facing ST



	1	2	3	4	5	6	7	8	9	10
Straight Forward	24	29	37	2	1	6	25	0	0	2
El-Force	87	4974	2149	251	179	3249	15300	17	8	29

FIGURE 11. Performance result when facing SSO65

responses might be different. Consequently, both invader drones tend to scatter. Because of the attractive force produced by a target area charge, the scattered invader drones tend to find the MDDs defense mechanism's weak point. Thus, MIDs can produce great damage to an area.

Although we have tested our proposed algorithm against various defense algorithms, we realize that our proposed method has been only compared to one invading algorithm, a Straight Forward invading algorithm described in [21]. In this paper, we cannot compare our proposed method to other invading algorithms because it is hard to find an open-source invading algorithm for Multiple Invader Drones vs. Multiple Defender Drones problems to the best of our knowledge. However, because we have significantly outperformed a general invading method, we can consider that our proposed method can be used as an effective attacking maneuver strategy in the Multiple Invader Drones vs. Multiple Defender Drones problem domain.

According to our experiment results and analysis, the comparative advantage of our work can be summarized as follows.

1) Our proposed method practically increases the damage produced by MIDs in most cases compared to SF when facing various defense strategies. It happens because our proposed method can adaptively adjust MIDs movement according to the situation and formation of MDDs.
2) Our proposed method does not require direct communication among the MIDs to perform coordination; thus, the execution time for adjusting maneuvers among the MIDs is relatively fast.
3) There is no drone coordinator/leader in our proposed method. Thus, our proposed method can still run properly when the number of MIDs increases or even decreases.
4) Our proposed method gets better results when the number of MIDs involved increases. However, our proposed method does not require a specific number of MIDs to perform well. It can work with any number of MIDs.

6. **Conclusion.** In this research, we develop an invading maneuver algorithm performed by a group of invader drones when striking an area. Our proposed method can generally increase the damage produced by MIDs toward a target area. According to our experiment, the exact number of MIDs and MDDs involved affects MIDs' damage more than the proportion of MIDs and MDDs. Based on our experiment, we can analyze that our proposed method performs well in various situations, even when the number of MIDs is lower than the number of MDDs in a battle. Our proposed method's primary benefit lies in its capability to find the weak point of MDDs maneuver without the need for MIDs to communicate with each other.

Currently, we can only test our experiment in a 3D simulation environment by comparing some available defense and attack algorithms for multiple drone battles. For future experiments, we plan to explore and develop many more defense and attack algorithms for Multiple Invader Drones vs. Multiple Defender Drones battles. By doing so, we hope that this research field can be more publicly opened to those researchers who have a passion for multiple drone movement strategies.

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