

On the Threat of Unmanned Aerial Vehicle as Weapon of Mass Destruction

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Received : November 2, 2020

Revised : December 9, 2020

Accepted : December 16, 2020

Abstract

Weapon of Mass Destruction (WMD) has a capacity to cause death and destruction on a massive scale and considered the most critical threat to any nation. In the past, only a few nations known to possess WMD since deploying it can be very costly. On the other hand, Unmanned Aerial Vehicle (UAV) has secured its future since the cost of ownership is drastically lowered and it has been used in many applications including terrorist and insurgent activities. The problem is even more pronounced if the UAV is tailored to deliver WMD attack. We provide an insight to this matter as well as investigate crucial effects under various circumstances in which UAV is equipped with WMD. The key metrics in focus are affected entities and coverage area of the UAV flight. We employ several UAV flight patterns and observe the impact on these key metrics. We demonstrate, through simulation studies, how various UAV flight patterns put their toll on the key metrics under clustered distributed and uniformly distributed population.

Keywords: UAV Flight Patterns, Coverage Area, Distributed Population, Weapon of Mass Destruction.

1. Introduction

UAV has gained its popularity in the recent years not only because it is more affordable than ever but also its versatility in several applications [1], [2]. For example, it can be used for aerial surveillance and reconnaissance, farm monitoring, aerial photography and film making, disaster management, wildfire tracking, structural inspection. In fact, UAV has

spawned its popularity from aerial photography and film making thanks to the ability to offer aerial perspective along with the freedom of movement. There is no need for roads or cables attached and can be deployed anywhere within the legal permit. At present, UAV almost already replaces human-operated aircraft in aerial photography and filming business since it not only provides a drastically cheaper solution but also eliminates the risk involved in operating an actual aircraft.

UAV can operate at various heights and distances. For the entry-level UAV, it can operate within seven miles and are mostly used by hobbyists. Short-range UAV, primarily used for espionage and intelligence gathering, has the operational range up to 90 miles. The General Atomics MQ-9 Reaper, primarily used by United States Air Force (USAF), is designed for long-endurance, high-altitude surveillance can handle the payload up to 1,700 kilograms and has the ability to travel over 1,900 kilometers with the service ceiling of 15 kilometers. These UAVs can be controlled from a distant location either directly by human inputs or autonomously operated through the pre-programmed flight path. Nevertheless, it is clear that UAV is a prominent recipe in both civilian and military domains and it has tackled arduous tasks, i.e., search and rescue in extreme climates, delivering attack behind enemy line, etc.

Since UAV is highly available and affordable, several concerns involving illegal uses of UAV are skyrocketing, ranging from misdemeanor to felony offense, depending on the territory the offense takes place. However, the major concern lies within the use of UAV for malicious purposes,

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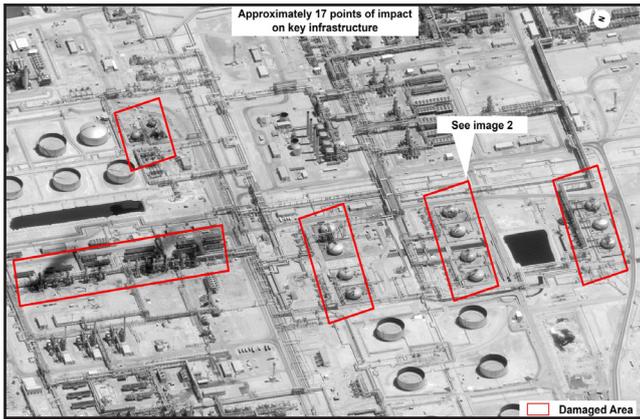


Figure 1. Damage to the infrastructure at Saudi Aramco's Abqaiq oil processing facility[3].

i.e., performing an attack on facilities and human population. Figure 1 shows the damage to the infrastructure at Saudi Aramco's Abqaiq oil processing facility after UAVs strike. It is believed that group of UAVs and cruise missiles were used for the attack. The attack caused large fires at the processing facility and were put out several hours later. The facilities were shut down for repairs which reduced Saudi Arabia's oil production by 50 percent, representing about 5% of global oil production. The collateral damage is also destabilization of global financial markets. Fortunately, there was no casualty for this incident. The outcome would have been devastated if the attack were to conduct on densely populated area in large cities or UAVs were equipped with more damage inflicted payload, that is, WMD.

In contrast to the traditional weapon, WMD is capable of annihilating and causing significant harm to humans as well as bringing a devastated damage to structures. It differs from traditional weapon in the way that it may not only cause sudden significant damage but also sustain a long-term effect to those who affected, i.e., radiological and biological WMD. The exact definition of WMD is hard to achieve. One can identified 20 different definitions of WMD coined by the United States government [4] as follow:

- WMD as nuclear, biological, and chemical (NBC) weapons.
- WMD as chemical, biological, radiological, or nuclear (CBRN) weapons.
- WMD as CBRN and high-explosive (CBRNE) weapons.

- WMD as CBRN weapons that cause massive destruction or kill large numbers of people.

- WMD as weapons that cause massive destruction or kill large numbers of people, and do not necessarily include or exclude CBRN weapons.

- WMD as weapons of mass destruction or effect, potentially including CBRNE weapons and other means of causing massive disruption, such as cyberattacks.

It is obvious that WMD can sustain a much larger damage than the tradition weapon and it can cause an even more concern if UAV is employed as a mean to deliver the payload. With the availability and portability of UAV, together with its ability to deploy without infrastructure, one can easily carry out an WMD attack using off-the-shelf UAV in large cities without alarming activity. For instance, the terrorists can equip UAVs with biological weapon, i.e., anthrax microbes, infectious viruses, and present themselves as tourists and allow themselves into the city without suspicion. They then proceed to launch an attack within the heart of the city and cause devastated damage. One of crucial questions is how the UAV flight pattern be in order to deliver the highest level of destruction. It can be programmed to fly in holding pattern, zig-zagging, or else. This question is critically worth exploring for both attacker and anti-attacker domains. This problem is tightly related to the coverage path planning problem, the operation of finding a path that covers all the points of a specific area.

In this work, we proceed to investigate on the damage caused by various UAV flight patterns. There are several UAV flight patterns known to public but information on how these UAV flight patterns have an influence on the damage once the UAV holds the WMD payload is very scarce. We put out attention on 4 different UAV flight patterns, Random Walk, Boustrophedon, Random Walk with Spiral, and Boustrophedon with Spiral.

The major contributions of our work can be summarized as follows:

- We provide an insight to the matter in which UAV is

generator. In other words, the UAV determines when to turn as well as how much to turn randomly. Obviously, this approach requires very little information from surroundings and it can travel on the same path it passes prior. Consequently, the random walk UAV flight pattern trades its simplicity over its coverage efficiency. One may conclude that the random walk UAV flight pattern has no place in today's application but we will see later on that under some circumstances, it offers indistinguishable performance for less requirements. Moreover, by the randomness nature built-in, its flight path is hard to predict and hence the countermeasure against it. The pseudocode for the random walk algorithm is shown in Figure 3.

```

Begin move forward
Let affected_radius = 5 meters
if collision detected then
    move backwards one affected_radius
    turn 180 degrees + random(+/-90 degrees)
endif
    
```

Figure 3. The Random walk UAV flight pattern.

3.2 Boustrophedon

Another UAV flight pattern under investigation boustrophedon. This method derives its name from the ancient Greek "ox plowing the field". Figure 4 illustrates the boustrophedon UAV flight pattern which composed of parallel path segments spaced by the width of the UAV's sensing range. This path guarantees complete coverage of a workspace in the absence of void. The boustrophedon UAV flight pattern requires marginal information about the topology as well as insignificant resource and computational power. However, the UAV performs its turn only at the boundary and continues its path throughout the coverage area. In other words, the UAV travels along the primary direction until it encounters an obstacle or a border then it performs another path along a direction perpendicular to the last direction and with a fixed pre-determined spacing. Since this method exhibits a sweeping motion, the UAV always travel on the new path, that is, the area will never be examined twice. Consequently, one may prefer the boustrophedon UAV flight pattern over the random

walk UAV flight pattern. However, it may take longer time to visit the destined point due to its nature of sweeping motion.

The pseudocode for the boustrophedon algorithm is shown in Figure 5.

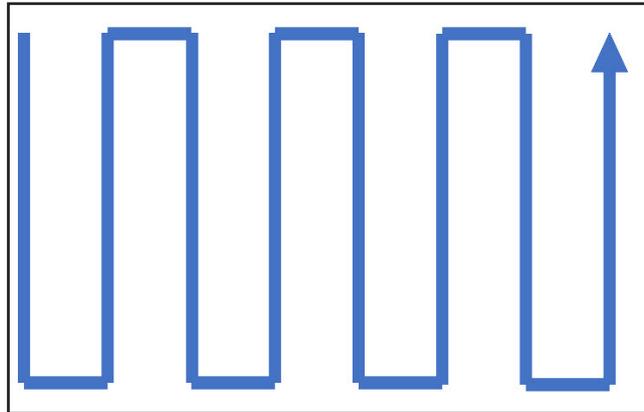


Figure 4. The boustrophedon UAV flight pattern.

```

Begin direction up
Let affected_radius = 5 meters
Let pathcount = 1
if collision detected then
    move backwards one affected_radius
    if pathcount is odd then
        turn 90 degrees clockwise
        move forwards one affected_radius
        turn 90 degrees clockwise
        pathcount = pathcount + 1
    else
        turn 90 degrees counter clockwise
        move forwards one affected_radius
        turn 90 degrees counter clockwise
        pathcount = pathcount + 1
    endif
else
    move forwards
endif
    
```

Figure 5. The boustrophedon algorithm.

3.3 Random Walk with Spiral

The random walk with spiral combines the spiral movement with the random walk mentioned earlier. In this method, the UAV performs its random walk flight path but when the UAV detects that there are multiple targets in its vicinity, it changes its flight to spiral path. This implies that in order to employ the random walk with spiral, the UAV must be equipped with onboard sensors to detect targets below. Consequently, this method requires higher resource and computational power

comparing to method mentioned earlier.

Once the UAV verifies that numbers of targets in its vicinity beyond the pre-defined threshold, it performs the spiral flight path to cover as many as targets possible. The spiral pattern can be continuous turns with increasing radius from the current position or rectangular with increasing length. During the spiral maneuver, the UAV keeps track of detected targets and once the rate of target detection falls below the pre-determined threshold, it returns to the point where it leaves off and continues the random walk flight path. Figure 6 illustrates the random walk with spiral UAV flight path.

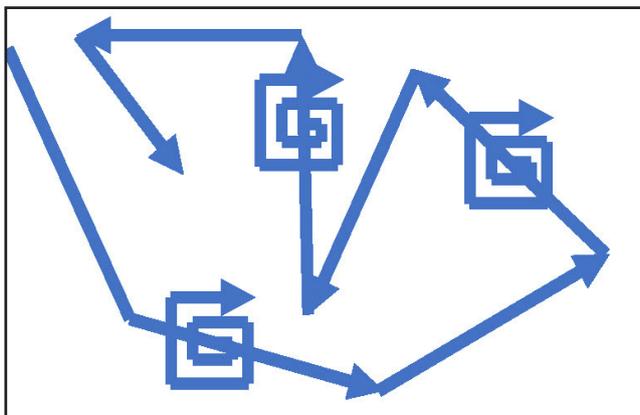


Figure 6. The random walk with spiral UAV flight path.

One may curious under which circumstance shall the random walk with spiral UAV flight path is called for. The answer lies within the feature of spiral maneuver. Consider the area in which population is not uniformly distributed, that is, the population is clustered. Figure 7 depicts the uniformly distributed population of 2000 in 400 x 400 m² area. It is clear that if the random walk with spiral UAV flight path is employed to the uniformly distributed population area, it may not benefit from the spiral maneuver since targets are dispersed. On the other hand, in case of the area in which population is clustered shown in Figure 8. It is obvious that the random walk with spiral UAV flight path can significantly perform much better since it can detect targets clumped in group and takes on them simultaneously thanks to the spiral maneuver.

In uniformly distributed population, each of a population are spaced more evenly. We can find uniformly distributed population in rural area or battlefield where individuals stake out and defend territories. In clustered distributed population, individuals are clustered in groups. This is commonly found in urban area or where social event takes place.

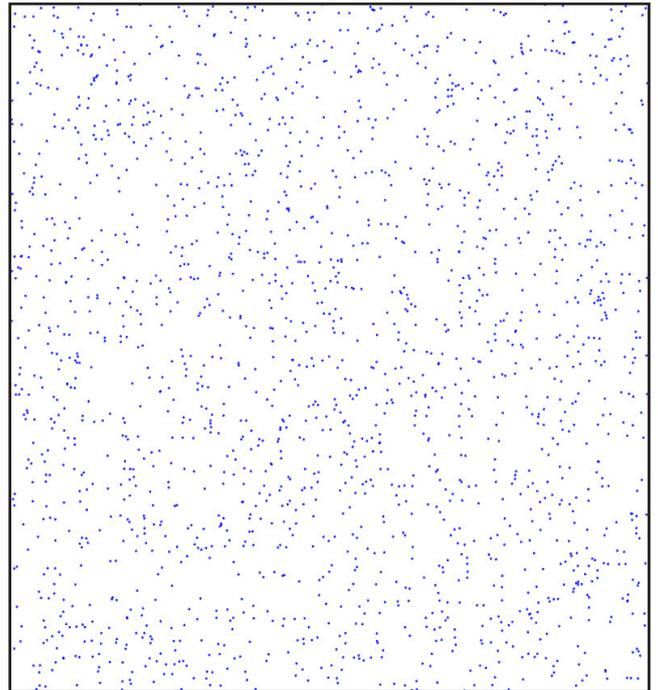


Figure 7. Uniformly distributed population.

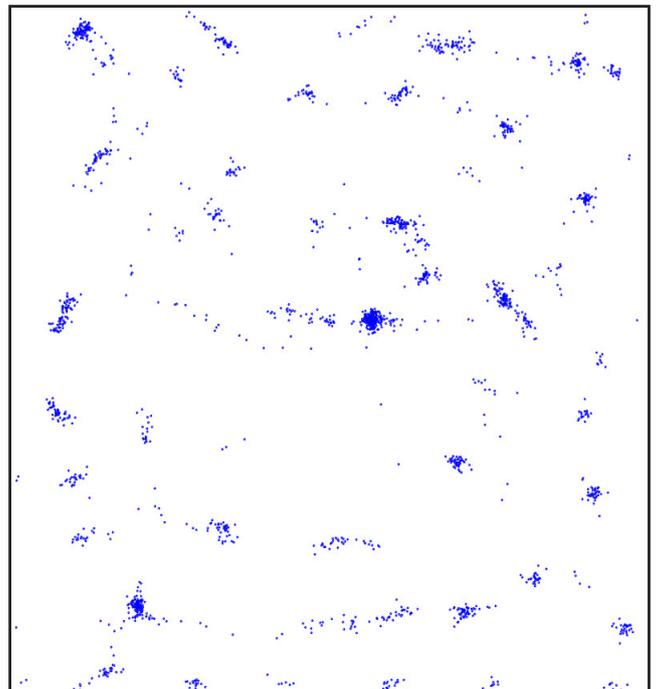


Figure 8. Clustered distributed population.

```

Let turn_radius = 90 degrees
Let spiral_time = 10 seconds
for time = 0 to spiral_time do
  while no collision do
    move forward
    turn turn_radius degrees clockwise
    decrease turn_radius
  end while
end for
  
```

Figure 9. The spiral algorithm.

Figure 9 shows the pseudocode for the spiral algorithm. Note that this pseudocode only represents the spiral maneuver which will be initiated once numbers of targets in its vicinity beyond the pre-defined threshold. Upon the completion of the spiral maneuver, it resumes the random walk at the point it leaves off.

3.4 Boustrophedon with Spiral

The boustrophedon with spiral combines the spiral movement with boustrophedon mentioned earlier. Similar to the random walk with spiral, the UAV performs its boustrophedon flight path but when the UAV detects that there are multiple targets in its vicinity, it changes its flight to spiral path. Again, this signifies that in order to employ the boustrophedon with spiral, the UAV must be equipped with onboard sensors to detect targets below. Consequently, this method also requires higher resource and computational power comparing to method mentioned earlier.

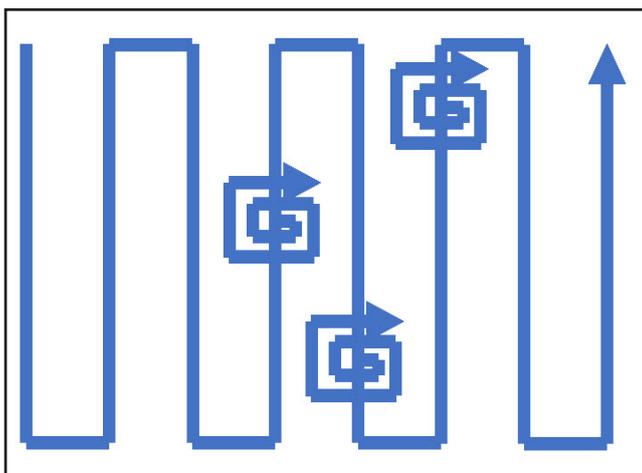


Figure 10. The boustrophedon with spiral UAV flight path.

Once the UAV verifies that numbers of targets in its vicinity beyond the pre-defined threshold, it performs the spiral flight path to cover as many as targets possible. The spiral pattern

can be continuous turns with increasing radius from the current position or rectangular with increasing length. During the spiral maneuver, the UAV keeps track of detected targets and once the rate of target detection falls below the pre-determined threshold, it returns to the point where it leaves off and continues the random walk flight path. Figure 10 illustrates the boustrophedon with spiral UAV flight path. The benefit of boustrophedon with spiral UAV flight path for various types of distributed population is also similar to the random walk with spiral UAV flight path.

The pseudocode for the spiral maneuver is shown in Figure 9 which is identical to one mentioned earlier. Again, this pseudocode only represents the spiral maneuver which will be initiated once numbers of targets in its vicinity beyond the pre-defined threshold. Upon the completion of the spiral maneuver, it resumes the boustrophedon at the point it leaves off.

4. Simulation Results

In this section, we thoroughly evaluate our findings using our custom simulator, developed in MATLAB. We investigate the effect of UAV flight time on affected sensors for various types of UAV flight patterns under both uniformly distributed and clustered distributed population as well as effect of UAV flight time on coverage area for various types of UAV flight patterns under both uniformly distributed and clustered distributed population. Unless specifically stated, the simulation time is limited to 900 seconds, the UAV speed is set to 12 m/s, and the area of deployment is 400 x 400 m². The number of iterations for each round of simulation is set to 10 and the result is obtained through the average value of 10 iterations. This is to prevent outliers from influencing the simulation results.

The UAV is said to be equipped with WMD and has the effective radius of 5 m. along its path. That is to say, anything within the vicinity of 5 m. from the UAV flight path is affected. The threshold for spiral maneuver is set to 5. We deploy 2000 sensors in both uniform and clustered fashion to mimic human population and observe the outcome.

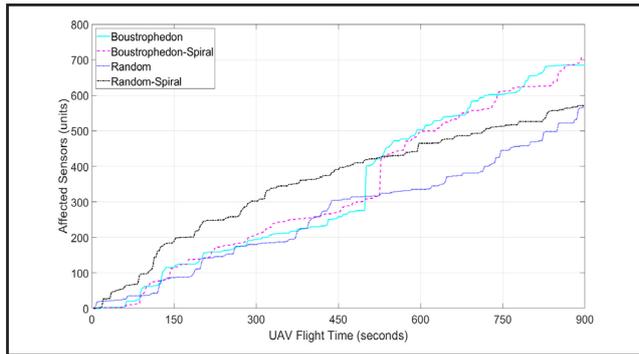


Figure 11. Effect of UAV flight time on affected sensors for various types of UAV flight patterns under clustered distributed population.

4.1 Affected Sensors

The first key metric under investigation is numbers of affected sensors when various UAV flight patterns are employed. Figure 11 shows the effect of UAV flight time on affected sensors for various types of UAV flight patterns under clustered distributed population. For the whole flight period, it is obvious that the boustrophedon-based UAV flight path is a clear winner since it delivers a larger amount of affected sensors, hence the higher damaged inflicted by WMD. However, if we consider only the first half of the flight, almost all UAV flight patterns offer roughly the same amount of affected sensors except from the random walk with spiral UAV flight path which provides a significant higher yield. This is not surprising since random walk UAV flight path is not limited to sweeping pattern and can traverse any direction which may find clustered sensors early. Additionally, even more sensors are affected thanks to the spiral maneuver incorporated in random walk with spiral UAV flight path.

Nevertheless, there is a flip side to that coin, we can see that the rate of affected sensors tends to diminish as time progresses. Again, this is not surprising as the random walk with spiral UAV flight path does not guarantee to take a new path, that is, it can travel on the same path it passes prior. Consequently, the UAV is not able to cover as much area and hence encounters less sensors. In fact, the performance of the random walk and the random walk with spiral is similar in the long term.

On the other hand, the boustrophedon and the boustrophedon with spiral UAV flight path reveal their

potential as time passes. In particular, these UAV flight paths guarantee to deliver a higher yield with time since they never take the same path twice and hence increasing coverage area and sensors encounter. Note that, the spiral maneuver offers marginal benefit in this case.

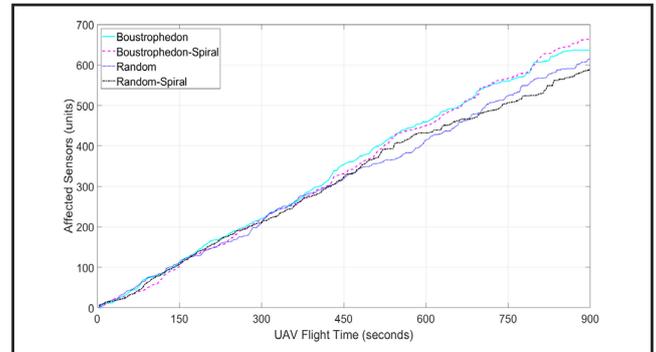


Figure 12. Effect of UAV flight time on affected sensors for various types of UAV flight patterns under uniformly distributed population.

It is also interesting to see how these UAV flight patterns perform under different circumstance. Figure 12 illustrates the effect of UAV flight time on affected sensors for various types of UAV flight patterns under uniformly distributed population. It is imperative to say that the spiral maneuver is not beneficial under uniformly distributed population. Actually, it may contribute to the degradation of the performance as seen on the random walk with spiral UAV flight pattern towards the end of the simulation. It is also clear that the boustrophedon and the boustrophedon with spiral UAV flight path show their potential as time passes. Again, if we consider only the first half of the flight, almost all UAV flight patterns offer roughly the same amount of affected sensors.

To sum it up, in order to deliver the highest level of damage for clustered distributed population, the boustrophedon with spiral UAV flight patterns is the most suitable choice and the spiral maneuver provides a marginal gain over the boustrophedon UAV flight pattern. On the contrary, in order to deliver the highest level of damage for uniformly distributed population, the boustrophedon UAV flight pattern is a clear winner and the spiral maneuver shall be avoided for the random walk.

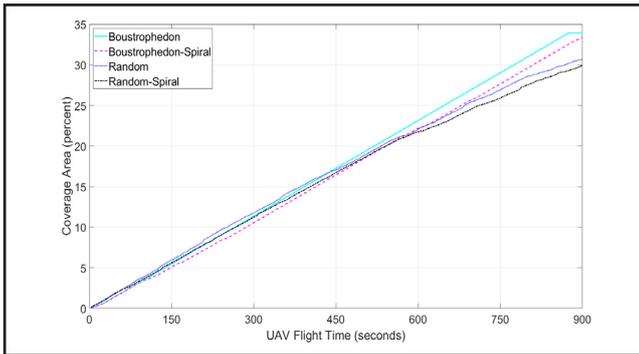


Figure 13. Effect of UAV flight time on coverage area for various types of UAV flight patterns under clustered distributed population.

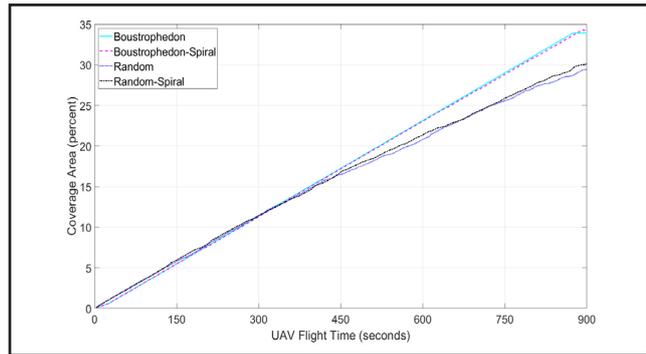


Figure 14. Effect of UAV flight time on coverage area for various types of UAV flight patterns under uniformly distributed population.

4.2 Coverage Area

The coverage area is another key metric under investigation. It is defined as the percentage of the area the UAV is capable of delivering WMD. In other words, the percentage of the area affected by the UAV flight path. In this work, the area within 5 m. radius from the UAV flight path is affected. The effect of UAV flight time on coverage area for various types of UAV flight patterns under clustered distributed population is shown in Figure 13. It is seen that the boustrophedon and the boustrophedon with spiral UAV flight pattern provide a higher coverage area when compared to the random walk and the random walk with spiral UAV flight pattern. The boustrophedon UAV flight pattern also exhibits a linear increase as expected since it follows the “ox plowing the field” pattern. Note that this is not the case for the boustrophedon with spiral UAV flight pattern as the spiral maneuver may occur frequently and hence decreases the coverage. However, decreasing in coverage area is not necessary translate to decreasing numbers of affected sensors. Lastly, if we consider only the first half of the flight, almost all UAV flight patterns offer roughly the same amount of coverage area Figure 14. shows the effect of UAV flight time on coverage area for various types of UAV flight patterns under uniformly distributed population. In this case, not only the boustrophedon and the boustrophedon with spiral UAV flight pattern distinguish themselves once the simulation goes beyond the first half but they also exhibits a linear increase. This implies that the spiral maneuver may never take place as sensors are distanced apart. On the other hand, the random walk and the random walk with spiral UAV flight pattern

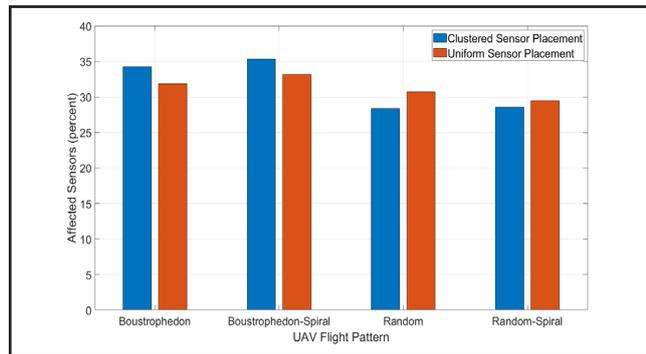


Figure 15. Effect of various UAV flight patterns on percentage of affected sensors.

offer a lower yield in coverage area as time progresses.

Figure 15 shows the effect of various UAV flight patterns on percentage of affected sensors. It can be concluded that for the clustered distributed population (clustered sensor placement), the boustrophedon with spiral UAV flight pattern outperforms the rest of UAV flight patterns and the spiral maneuver plays a major role in providing an extra performance gain over the boustrophedon without spiral UAV flight pattern. On the contrary, the random walk and the random walk with spiral UAV flight pattern offer a similar performance and obviously there is no performance gain from spiral maneuver.

For the uniformly distributed population (uniform sensor placement), the boustrophedon with spiral UAV flight pattern still surpasses the rest of UAV flight patterns and the spiral maneuver plays a key role in providing an extra performance gain over the boustrophedon without spiral UAV flight pattern. Surprisingly, the random walk UAV flight pattern outmatches the random walk with spiral UAV flight pattern and clearly the spiral maneuver does more harm than good.

5. Conclusions

WMD is known for its ability to deliver a damage for human and structures on a massive scale and considered the most critical threat to any nation. At present, the availability and affordability of UAV make it a good candidate in many applications including terrorist and insurgent activities. The problem is even more pronounced if the UAV is tailored to deliver WMD attack. We provide an insight to the matter in which UAV is equipped with WMD and tailored to deliver WMD attack. Moreover, we demonstrate, through simulation studies, how various UAV flight patterns have an effect on the affected entities and coverage area of the UAV flight under clustered distributed and uniformly distributed population. The studies show that the boustrophedon UAV flight pattern deliver the highest level of damage in both clustered and uniformly distributed population. Additionally, the spiral maneuver offers an additional performance gain for all UAV flight patterns except the random walk under uniformly distributed population.

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