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Road Mapping the Future of Counter-Drone Technology

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Abstract: Drones are ubiquitous on the modern battlefield, and their usage is expected to increase. As such, most modern militaries have developed and fielded counter-drone technology to neutralize enemy drones. However, given the rapid growth of the commercial and military drone markets, counter-drone technology is struggling to keep pace. This analysis creates a technology roadmap for counter-drone systems looking at near-, mid-, and long-term solutions. This roadmap requires projecting the future of the commercial and military drone markets based on advancements in the underlying technology (e.g., artificial intelligence, swarm technology). Near-term counter-drone technology will use advanced tracking with kinetic weapons coupled with electronic warfare. In the mid-term, counter-drone systems will use hunter drone swarms that accompany units and attack enemy drones. The long-term solution augments the mid-term solution with aircraft-based and space-based directed energy weapons. These projections help guide development efforts as militaries attempt to neutralize the drone threat.

Keywords: Roadmap, Technology Forecasting, Drone, Counter-Drone

1. Introduction

Unmanned aerial vehicles (UAVs), or drones, are aircrafts flown either autonomously or remotely controlled without a pilot on board. Many military experts forecast that future conflicts will see drones playing an increasingly important role on the battlefield (Army UAS CoE, 2009). Over the last decades, many modern militaries have fielded a range of UAVs to their warfighters. Even insurgent groups such as ISIS adopted the use of cheap, commercially-available quadcopters. Given the proliferation of drone technology, militaries have had to evaluate how to neutralize enemy drones. Meanwhile, the commercial drone market is advancing at a rapid pace due to large technology development efforts in consumer electronics and artificial intelligence. The military drone market has leveraged the advances from the commercial sector, allowing for its rapid growth and evolution as well. As such, counter-drone technology is struggling to keep pace with drone technology, having been historically responsive in nature.

This analysis attempts to create a roadmap for counter-drone technology by predicting the states of the commercial and military drone markets, then identifying the technologies that will be available. The paper begins by identifying the trends in the drone markets and the underlying technology areas. It then presents roadmaps for the near-, mid-, and long-term solutions for counter-drone technology. These roadmaps then provide insight into development efforts and priorities necessary to ensure that counter-drone technology is not out-paced by drones.

2. Current UAV Trends

While originally a field dominated by the military, drones are becoming increasingly available to average, every-day consumers. Drones are now commonly used for entertainment, agriculture, and private businesses. Many industries are looking to drones to replace jobs typically performed by humans. The evolving technologies and growing market have driven down the price and increased the accessibility of drones, introducing immense security threats and new vulnerabilities. The rising prevalence of drones with improved capabilities demands well-developed counter-drone technologies to protect infrastructure, populations, and general security.

2.1 Commercial Drone Market

Drones offer a cheaper alternative to helicopters for professional photography and videography, assist in humanitarian operations and help groups in disaster zones, and survey and spray crops for the agriculture industry (Sayler, 2015). The "hobbyist drone" category refers to those easily acquired by the average consumer and do not require extensive training to operate. Generally less than a few thousand dollars, these commercial off-the-shelf (COTS) drones often come either pre-assembled or in a few parts ready for assembling. They have ranges of a few kilometers and can perform aerial surveillance and payload deliveries. Many COTS drones offer GPS that provides autonomous flight and return-to-home options. These readily available and user-friendly aircrafts offer performances that previously only existed within major world power's military technologies.

The global market for COTS drones continues to expand rapidly. Predictions for market trends vary, with some estimating as high as $1.7 billion by the year 2025, but all suggest the same general trend of strong growth (West, 2015). SZ DJI Technology Co., the largest manufacturer of COTS drones across the globe, offers drones equipped with advanced and unprecedented technologies. DJI manufactures roughly half of all drones registered in the U.S. and Japan (Sayler, 2015). Due to the DJI dominance of the global drone market, China produces the majority of the world's drones (Erikkson and Lundin, 2020). There are over 400 drone manufacturers in China, and 8 out of the world's top 13 COTS drone manufacturers are Chinese. China created drone schools that offer students courses to pursue a drone pilots license to bridge the existing gap, inferring their intentions to make greater use of this space.

The increasing capabilities of hobbyist drones has created opportunities for them to be used for military and terrorist endeavors. Most hobbyist drones can carry small payloads, including video cameras capable of providing surveillance (Sayler, 2015). These hobbyist drones are being used by individuals and nation-states alike. Pakistan, for instance, acquires drones from US and Chinese manufacturers and employs them for Indian border surveillance (Peri, 2015). Other payloads may include more deadly items such as explosives or chemical and biological agents. For example, ISIS insurgents would drop grenades or mortar rounds onto Coalition forces using DJI quadcopters.

2.2 Military Drone Market

More than ninety militaries and non-state actors use drones; of these, over thirty of them are developing or fielding armed drones (Sayler, 2015). Non-state actor groups, such as Libyan rebel groups, actively employ drones for surveillance purposes and are not far out from the capabilities necessary for drone attacks with deadly outcomes.

The midsize military and commercial drone categories consist of those not available to the average consumer due to infrastructure requirements or high cost. These drones range in cost anywhere from $100,000 to millions. They differ significantly from hobbyist drones in their range and endurance; these drones may last up to an hour and travel farther than 10 kilometers. They can carry advanced optics and are most often used for surveillance purposes, but they are predicted to move towards carrying lethal munitions. Many systems are capable of autonomous flight and use radar to detect improvised explosive devices (IED), map all-weather terrain, and track targets. Some even incorporate electronic intelligence and jamming abilities that can disrupt the communication of other threats.

Large military-specific and stealth combat drones refer to drones with highly advanced and sophisticated technology, a greater range and endurance than the previous drone categories, and a greater capacity for payloads. Note that these systems are still vulnerable to enemy air defense systems (Sayler, 2015). These drone categories are only available to major militaries and are the product of substantial development efforts. The US military uses numerous systems including the MQ-9 Reaper, which carries up to 3,750 pounds, travels just under 2,000 kilometers, costs $56.5 million, and functions to collect intelligence or perform strikes against time-sensitive targets (US Air Force, 2015). Between 2010 and 2015, the US Air Force doubled the MQ-9's flight time nearing that of a typical F-16 fighter jet (Erikkson and Lundin, 2020). The Russian military developed the Sukhoi S-70 Okhotnik-B that has a range of 4,000 kilometers and travels at speeds approaching the speed of sound (Rogoway & Trevithick, 2020). The Chinese Air Force developed the Wing Loong. Used for surveillance and aerial reconnaissance missions, it is also fit with weapons and can perform combat operations (AirForce Technology, 2019).

2.3. Current Counter Drone Technology

The proliferation of drone technologies has resulted in the need for advanced counter drone systems to protect infrastructure, populations, and security. The most common method is geofencing (Looze *et al.*, 2016), whereby a drone cannot enter restricted airspace. This is incorporated into many COTS products, including DJI; however, only a limited number of areas are geofenced, numerous platforms do not include geofencing limitations, and code patches are available to defeat it. As such, there are more sophisticated counter drone measures available.

Counter-drone systems are typically classified as stationary, portable, or aerial (Souli *et al.*, 2020). The systems detect and intercept threats using a variety of techniques. Stationary systems are useful because their constant access to power offers increased range. However, their limitations include the risk of interfering with legitimate telecommunication systems and the threat to public health. Portable counter-drone systems have a mobility advantage but are often small and simplified with a limited range that requires an operator to manually aim the system. Aerial systems are installed on drones and can patrol areas

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to detect and neutralize other malicious drones. Although they require complex algorithms, the aspect of close proximity allows these systems to have minimal wireless interference.

The steps to counter a drone include detection, identification, and neutralization. Detection is the most difficult step in the process. Radar networks often cannot differentiate small drones from birds. There are two types of detection: active detection, such as air defense radars and radio, and passive detection, such as acoustic sensors and coherent locators (Peri, 2015). Most COTS systems use a combination of active and passive detectors. Examples include Gryphon Sensors and Dedrone. The active detection can be radio, sound, or light-based. The passive detections use optical, sound, and radio-frequency (RF) sensors. RF-spectrum scanning is used mostly for long distance while shorter distance passive detection uses an acoustic approach. One company, Drone Shield, developed a product that identifies incoming drones up to 1000 yards away using a network of acoustic sensors. The product then identifies that threat and shoots a net gun that traps the aircraft.

The second step, identification, is the easiest step in the process and can be accomplished through electro-optic or infrared sensors, electronic intelligence, and acoustic sensors (Peri, 2015). Precision is vital in this step in order to ensure appropriate countermeasures.

The two most common neutralization methods are the kinetic kill and jamming (Peri, 2015). Kinetic kills refer to physical attacks such as shooting a drone down with a rifle or using anti-aircraft missiles and fighter aircraft. These methods are often the most reliable and preferable. Limitation exists for smaller, low flying drones that require extreme shooter expertise and accuracy. Larger drones are easier to target through the use of missiles, but they can also fly at higher altitudes making it much more difficult. One surface-to-air missile developed by Bharat Dynamics can shoot down drones up to 25 kilometers away. Kinetic kills also include the use of lasers to burn and disable drones which is a more cost-effective option, and laser weapons are currently under development.

The second form of neutralization, jamming, is a safer option but proves more difficult for modern drones. Jamming targets threats through an electromagnetic signal that overwhelms the system's controls. Plain jamming may remove the drone from the restricted area whereas spoofing can overtake the controls. GPS spoofing is considered an effective option for hostile drones because it removes the threat and allows friendly forces to analyze enemy systems.

3. Roadmapping Methodology

Roadmapping a system requires trying to predict the future states for a given technology, in this case counter-drone technology (Phaal, 2003). These future states are based on the future states of other systems, namely the commercial and military drone markets. As depicted in Figure 1, these three technology areas are interrelated and allow for the prediction of the requirements for the counter-drone systems. The previous section outlined the status quo for each of these areas. In turn, given the influence arrows shown in Figure 1, the near-term, mid-term, and long-term technologies associated with each layer can be forecasted. For this analysis, near term is considered 2-4 years from the present, mid-term is 4-8 years out, and long-term is 8-12 years out.

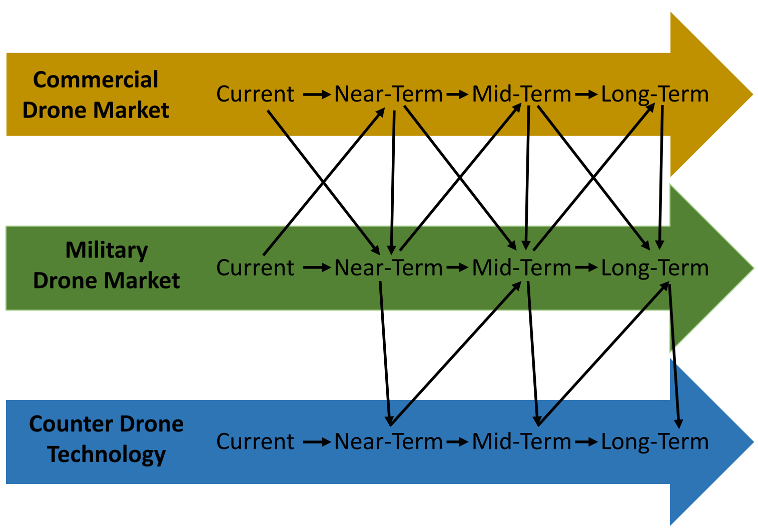

Figure 1. Roadmapping methodology that considers the commercial drone market, military drone market, and counter drone technology.

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The commercial drone market has experienced unprecedented growth in the past decades. The growth has out-paced military drone development in certain areas, such that military drones will be incorporating technology from previously developed commercial drones. An excellent example is the Prox Dynamics Hornet, which used a commercial small remote-helicopter platform to provide American infantryman a small UAV for performing reconnaissance. Additionally, current commercial drones are being militarized, especially by insurgent groups, such as ISIS that used commercial quadcopters to drop grenades on Coalition solders.

Although the military drone market is capitalizing on the advances from the commercial drone sector, the military market is still leading in a number of technology areas including resilience and security. These military developments will help drive the next generation of commercial drones. Meanwhile, the counter-drone technology will naturally follow the state of technology for the military drone market.

The commercial drone market for the near-term can be forecasted based on the technology areas discussed in Section 4. Combining these advances with the current state of the military drone market, the near-term military drone market and counter-drone systems can be predicted. The near-term states are then used to determine the mid-term states, which in turn are used to predict the long-term states. Multiple experts in the field of military technology, drones, and computing were consulted to define the current state and trends as well as to help predict future states.

4. Underlying Technology Areas

4.1. Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning are now incorporated into many drone and counter-drone systems. When used for drones, AI assists flight by using sensors to collect data, feeds the data to machine learning models, and develops a plan of how to respond and which objects to target or avoid.

AI-powered counter-drone systems can autonomously detect, track, and combat drones. These systems collect data using radar and sensors and then use machine learning and complex recognition patterns to analyze the data and identify threats. They then counter drones through soft and hard kills or jamming. The systems also can generate analysis reports following operations that assess the threat activity patterns. These AI-driven systems, available in both fixed and mobile options, are as small as 20 pounds.

The largest implication for implementing AI and machine learning into drone and counter-drone systems is that it eliminates the need for a system operator. This makes both the systems more effective without the presence of human error throughout operations. Additionally, it allows one operator to utilize multiple systems simultaneously without the need to constantly fly, monitor, or direct operations. Furthermore, systems are more efficient as data can be processed and applied in real-time allowing the system to adapt to conditions and carry on the mission.

4.2. Computer Vision and Object Recognition

Computer vision (CV) is a form of AI that allows computers to analyze images to understand the visual world (Brownlee, 2019). CV plays a significant role in the autonomous flight abilities of drones. CV reproduces human vision capabilities to extract information from images, including object detection and recognition.

For drones, object detection is important for two reasons. First, it assists in flight to avoid collisions or unwanted detection. Second, object recognition means that drones can autonomously detect and track targets without the help of an operator's eyes-on identification. An operator must only decide and instruct what the target is, and the drone can carry out the remainder of the mission. On the other hand, object recognition is important for counter-drone systems because it discriminates surroundings to identify when a threat is in sight if not detected through other means. This again eliminates the need for an operator to have eyes-on identification and allows to the system to operate autonomously. It proves for a more efficient system when it is not limited to relying on human abilities.

4.3. Swarm Technology

Swarm technology describes the capability of drones to act autonomously using shared information, characterized specifically by inter-drone communication (Kallenborn, 2018). Swarms have a variety of conflict applications such as search and rescue operations, mass-attacks, or building walls of defense. Drone swarms are an especially dangerous form of technology used for drone attacks because they could inflict mass harm with little control or care for target discrimination to protect innocent bystanders. Pairing together drones of different types, sizes, and capabilities implicates the complex and deadly attacks that will be made possible through swarm technology.

Additionally, drone swarms could prove extremely difficult to defeat with counter-drone systems when employed by adversaries. A kinetic kill approach seems unlikely when scaled to swarms in the hundreds or thousands. Furthermore, given a diverse array of drone systems, it is likely that a counter-drone will need to employ more than one countering method to address the different threats. The most effective method will most likely incorporate jamming to disable the communication between the drone before attacking them individually.

4.4. Advances in Consumer Electronics

Over the past three decades, there has been a massive explosion in the field of consumer electronics. Indeed, today's smart phones have more processing power and memory than computers from a decade ago. This trend is expected to continue, following Moore's Law, which states that the number of transistors in an integrated circuit (IC) doubles every two years (Courtland, 2017). As such, consumer electronics are getting smaller, more powerful and cheaper. For example, the Raspberry Pi system is a fully functioning computer that can connect to a computer and interface, but only costs $60. With an antenna and code that can be downloaded from online repositories, the system can be turned into a basic software defined radio. The development of radio technology, especially software defined radios, had historically been limited to defense and communication labs; however, now a hobbyist has this capacity.

This proliferation of technology plays a large role in the commercial drone market. The processors, sensors, and actuators on a drone are becoming substantially cheaper, allowing a normal person to have access to sophisticated systems. Take for example the DJI Mavic Air, which can be purchased from Amazon for $600. Moreover, this proliferation in technology is allowing for significantly advancement in autonomy algorithms. Rather than having a select group of scientists in a lab working on developing the code for autonomous flight, millions of hobbyists, students, and professional roboticist develop and share code over online repositories. This crowd sourcing of algorithms allows for the development of more advanced and robust flight control systems.

5. Roadmap

5.1. Near-Term Counter-Drone Technology

Near-term counter-drone technology will be driven primarily by the technology implemented in military drones, to include commercial drones used for military applications. The commercial drone market is projected to see increased capability paired with a decreasing price. This will result in more readily accessible drones that are significantly more capable. Drones will have higher payload capacities, longer ranges, and will use a combination of fixed wing flying with vertical take-off and landing (VTOL). They will be programmed to include collision avoidance, especially in the package delivery sector, as it is not feasible for humans to control each individual flight path and maintain situational awareness on a mass scale. Instead, collision avoidance must be built into an algorithm of each drone which will aid not only their own flight but also improve the effectiveness and abilities of drone swarms. Additionally, drones will operate with increased autonomy, lowering the necessary intervention of humans allowing for a greater number of more complex missions to occur simultaneously.

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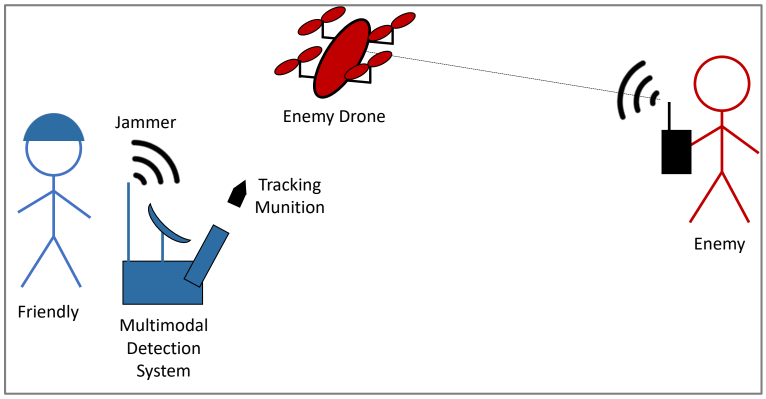

Figure 2. Depiction of near-term counter-drone system.

The military drone market will see similar developments as the commercial drone market but will also include the implementation of drones at a tactical level. This includes loitering munitions which have potential for significant impact given the projected payload capacities. The longer range will allow units to conduct missions at further distances and longer durations. Collision avoidance and drone autonomy that improve drone swarm performance will lead to missions conducted by drone swarms rather than soldiers.

Figure 2 depicts the near-term counter-drone system. The system will need to incorporate multi-modal detection to account for the complexity, variability, and capabilities of future UAS. This will include vision, audio, and radio frequency (RF). Counter-drone technology will also include tracking munitions and jamming to employ after positive detection and identification of systems.

5.2. Mid-Term Counter-Drone Technology

The mid-term commercial drone market will expand upon trends in the near-term projections with an emphasis on AI. The combination and development of these tools will take human intervention mostly out of the equation of drone tasks. Furthermore, they will increase the collaboration between drones to include an increased amount of swarm technology. The expansion of AI and machine learning will also improve the successful identification of other drones and will increase the security of systems as they learn from previous threats that attack not only themselves, but, through collaboration, other friendly systems. Similarly, the military drone market will capitalize on improved AI and machine learning to aid in target detection and threat detection. This, combined with enhanced vision, will expand the spectrum of military drone missions while increasing the success rates and security.

In the mid-term, counter-drone technology will see loitering seek-and-destroy drone swarms that await threats to attack and do not require human intervention to employ, detect, or defeat. A depiction of this system is shown in Figure 3. Given increased ranges, these systems will accompany soldiers on missions and provide a mobile security perimeter around the soldier against other drones. Future technologies will also see the ability to compromise enemy swarm networks to disable functionality as well as track and attack the enemy network or source.

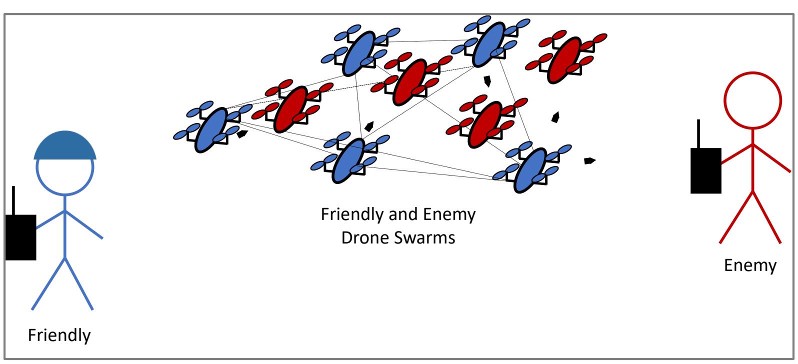

Figure 3. Depiction of mid-term counter-drone system.

5.3. Long-Term Counter-Drone Technology

Long-term drones will be able to leverage advances in AI and computing. The long-term commercial drone market is projected to see deploy-and-forget drones which are capable of travelling at very high-speeds, potentially hypersonic. Several larger militaries have already developed drones that can move at these speeds, although they lack significant capability past delivering a warhead. This technology over the next decade will be integrated with swarm technology and autonomy to create a very lethal military drone. These drones will also likely have larger ranges and increased autonomy along with integrated countermeasures against counter-drone technology.

The counter-drone technology now requires a "defense-in-depth" approach as shown in Figure 4. At the outer edge, the system consists of a series of airborne and space-borne systems that use directed energy weapons to destroy, disrupt, or degrade the drone (US Air Force Research Lab, 2021). However, given the speed and number of drones, it is unlikely that this defense layer will be able to neutralize every drone. As such, there will be a second layer of defense, which will be similar to that of the mid-term system. In this case, a swarm of drones will accompany the soldiers, share information amongst themselves and with the first layer defense, and neutralize any drone that is able to get past the initial defensive line.

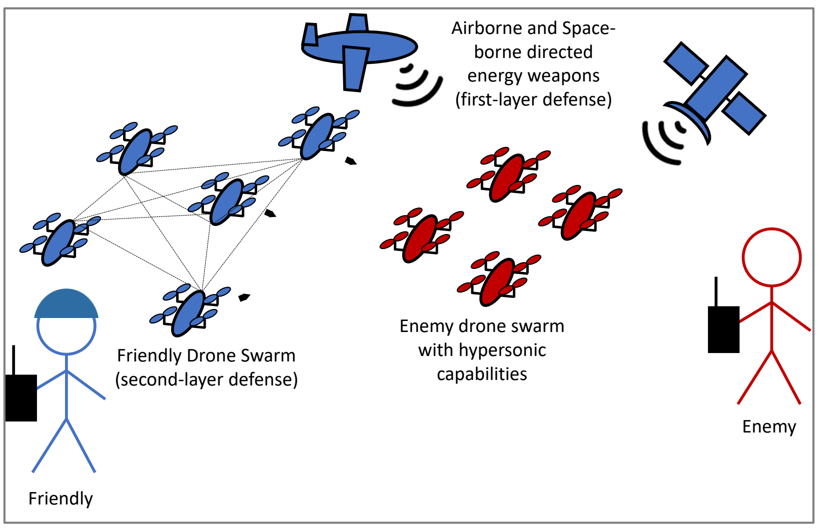

Figure 4. Depiction of long-term counter-drone system.

6. Analysis of Roadmap

Technology roadmaps are inherently useful in highlighting technology trends and the implications that they have for a market, in this case counter-drone technology (Leslie, 2018). The roadmapping exercise identified major technology areas that will play a role in this area. These technologies include artificial intelligence and swarm technology. However, since both of these technologies will play a role in military drone technology as well, it is important that counter-drone technology stay ahead of it. Since militaries are already investing heavily in these areas, they need to ensure that the research developments also support counter-drone efforts.

They also allow for the identification of technology gaps that require investment to allow for the implementation of the necessary systems. In this case, the long-term counter-drone system requires the use of space-based and airborne directed energy weapons. Although directed-energy weapons are already in usage for counter-drone applications, they lack the long range necessary for neutralizing very fast-moving drones. While the weapon itself can have a substantial range, they simply cannot detect or track a small drone at distance. As such, for this counter-drone system to be effective, they require advancements in detection and tracking algorithms.

Another technology gap is using the weapon system to exploit the enemy network (i.e., find the operator or source of the drone and neutralize them in addition to the drone). Current signal intelligence systems allow for the exploiting of networks; however, they are large, bulky, and require a human-in-the-loop. Advancements in the commercial sector will likely not result in improvements in this technology since it is a purely military application. As such, this is another area that requires investment.

The third technology gap is related to the range and duration of drones used in a counter-drone defense. Smaller drones, which would likely accompany units during tactical operations, are somewhat limited in terms of range and endurance. For the drones to accompany the unit, they would require autonomous recharge options, where they autonomously fly to a charging dock, recharge, and then rejoin the swarm. Alternatively, new battery chemistries and novel flight systems could potentially boost the range of the drones.

Technology roadmaps also allows for the analysis of different military tactics (Mittal & Davidson, 2020). This roadmapping exercise found that given the rapid advancements in drone technology, counter-drone systems should use a tiered approach that rely on multiple layers of defense against drones. While a single-layer system works on the near- and mid-term, as the technology advances, a single defensive layer would be inadequate. The roadmap identified that the mid-term solution can still be used in the long-term, but with the addition of a second layer of defense that can neutralize some of the drones at a further distance. As such, the mid-term solution should be designed with the flexibility of accommodating the additions from the long-term solution, resulting in a substantial cost saving.

7. Conclusions

Drones are playing an increasingly important role on the battlefield, and future battles will likely be determined in part by which military is better able to counter its adversary's drones. Given the rapid advancements in this area, it is critical to predict the future requirements for counter-drone technology on the near-, mid-, and long-term. This analysis used a technology roadmapping approach, which analyzes the current state of a market, its underlying technologies, and the related markets, to predict the future state of a system.

This paper presented a technology roadmap for counter-drone technology based on projections for the future state of the commercial and military drone markets. It included an analysis in the underlying technology areas to include artificial intelligence, computer vision, swarm technology, and consumer electronics. The analysis found that the near-term counter-drone technology will use advanced tracking with kinetic weapons coupled with electronic warfare. In the mid-term, these systems will use hunter drone swarms that accompany units and attack enemy drones. The long-term solution augments the mid-term solution with aircraft-based and space-based directed energy weapons. These projections helped to identify critical technologies that can help guide development efforts, as militaries attempt to neutralize the drone threat.

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