

# 2022 INTERNATIONAL JOINT RESEARCH PROJECT

## Nuclear Escalation Risks on the Korean Peninsula and the ROK-US Response

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## Changes in International Environment and the Development of ROK-U.S. Defense Space Force

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## Application of Drone to Military Operations in Industry 4.0 - Theory and Algorithms.

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## **International Joint Research Project 2022**

Published by The Research Institute for National Security Affairs

Publication Date: December 2022

Address : 1040, Hwangsanbeol-ro, Yangchon-myeon, Nonsan-si, Chungcheongnam-do  
33021, The Republic of Korea

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E-mail: pskee@korea.kr

Book Design: Kyung-Sung Publishing Company

ISSN: 2982-7175

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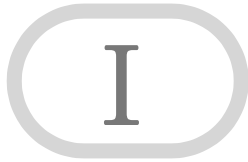
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# **Nuclear Escalation Risks on the Korean Peninsula and the ROK-US Response**

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## I. Introduction

For much of 2022, the risk of nuclear escalation on the Korean Peninsula has intensified, showing few signs of stopping. The situation is primarily driven by ostensible changes in both the will and ability of the Democratic People's Republic of Korea (DPRK) to credibly threaten nuclear strikes against the Republic of Korea (ROK) and the United States. Concerns about nuclear use hinge on a foreboding combination of at least three factors. First, Pyongyang has been decisively engaged in the “most active period of missile tests in its history,” maturing its means to deliver nuclear warheads of various types to various and increasing ranges.<sup>1)</sup> Second, for months a seventh North Korean nuclear test -- the first in five years -- has been perceived as “imminent.”<sup>2)</sup> Analysts argue such an event would allow the Kim Jong Un (KJU) regime to improve designs of tactical or hyper-yield nuclear weapons. Finally, at the Supreme People's Assembly in September, Pyongyang updated its declaratory policy on nuclear weapons employment, codifying the regime's right to launch pre-emptive strikes in case of an imminent attack against its leadership.<sup>3)</sup> While all of this behavior could be aimed at intimidating Seoul and Washington, or at bolstering regime support amidst pandemic- and sanctions-driven hardship, the risk that Pyongyang ultimately delivers a nuclear threat cannot be taken as anything less than real.<sup>4)</sup>

In tandem with advancements in North Korean nuclear capability, however, one of the primary vehicles for responding to that threat, the ROK-US alliance, has placed itself on firmer footing. For the first time in several years, DPRK's missile tests were reciprocated by launches from the alliance, and joint exercises continued in spite of Pyongyang's protests.<sup>5)</sup> These actions follow renewed commitment by

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1) “Secretary of Defense Lloyd J. Austin III Remarks Welcoming the Republic of Korea's Minister of National Defense, Lee Jong-Sup, to the Pentagon,” US DoD, July 29, 2022.

2) “Department Press Briefing,” US DoD, May 6, 2022.

3) Min Joo Kim, “North Korea codifies right to launch preemptive nuclear strikes Image without a caption,” *Washington Post*, September 9, 2022.

4) Hyun-jin Kim, “Seoul says N. Korea will self-destruct if it uses nukes,” AP News, September 13, 2022.

5) Michelle Ye Hee Lee, “U.S. and South Korea respond to North Korean launch with 8 missiles of their own Image without a caption,” *Washington Post*, June 6, 2022.

Seoul and Washington to bolster allied deterrence and defense capabilities and prioritize allied military readiness.<sup>6)</sup> The means by which the ROK-US alliance can reinforce stability on the Peninsula is thus expanding, along with the resolve to use the “full range” of capabilities as needed.<sup>7)</sup>

This article evaluates North Korean nuclear capabilities and reviews select scenarios of nuclear use, including deliberate and unintended nuclear escalation. It also examines the ROK-US alliance posture for potential responses to such escalation. More broadly, the ROK-US relationship provides an important lens through which the utility of extended nuclear deterrence can be examined.

## II. Understanding the Risk of DPRK Nuclear Escalation

### 1. DPRK intent and capabilities with respect to nuclear weapons

#### 1) Capabilities

Slowly but steadily North Korea has acquired and advanced its ability to threaten targets across Northeast Asia, and potentially in the United States, with nuclear use.<sup>8)</sup> This capability centers on the simultaneous, ongoing development of a stockpile of nuclear warheads – with enough fissile material to accommodate 45-55 nuclear weapons of relatively low yield (10-20 kilotons)<sup>9)</sup> – and of an array of delivery

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6) Take, for example, the reactivation of joint field training exercises and high-level consultative bodies like the Korea-U.S. Integrated Defense Dialogue. “Joint Press Statement for the 21st Korea-U.S. Integrated Defense Dialogue,” US DoD, August 17, 2022.

7) “Press Gaggle by Press Secretary Karine Jean-Pierre En Route Columbus, Ohio,” The White House, September 9, 2022

8) For a recent characterization of other DPRK capabilities and how they may threaten the ROK-US alliance, see [https://www.rand.org/pubs/research\\_reports/RRA2026-1.html](https://www.rand.org/pubs/research_reports/RRA2026-1.html)

9) Hans M. Kristensen & Matt Korda, “North Korean Nuclear Weapons 2022,” *Bulletin of the Atomic Scientists*, 78:5(2022), 273-294. The *Bulletin's* estimate aligns with Dr. Siegfried Hecker's assessment that a stockpile of 20 to 60 weapons is possible, with the most likely number being 45. 38 North, “Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker,” 38 NORTH, April 30, 2021. For a U.S. government perspective, which arrives a similar conclusion, see the 2021 Defense Intelligence Agency (DIA) report on North Korean Military Power (NKMP).

platforms, with Pyongyang allegedly possessing some 700 to 1,000 ballistic missiles.<sup>10)</sup>

Though firm evidence tends to be difficult to come by, an active fissile material production enterprise appears to underlie this threat. North Korea reportedly continues to produce both highly enriched uranium (HEU) and plutonium for weapons purposes. In terms of uranium enrichment capabilities, North Korea is believed to operate centrifuge facilities at the Yongbyon nuclear complex and at least one other location.<sup>11)</sup> With respect to plutonium supply, North Korea has tended to rely on Yongbyon's 5 MWe plutonium production reactor and Radiochemical Laboratory reprocessing plant, but may utilize the Experimental Light Water Reactor in the future.<sup>12)</sup> Such activities suggest that North Korea has the ability to continue expanding the number and type of nuclear warheads in its possession.

North Korea conducted six nuclear tests from 2006 to 2017. Despite Pyongyang's subsequent declaration in 2018 that DPRK was now a nuclear state and no longer had a need for testing, monitoring organizations have recently observed preparations for such an event. Analysts offer that a seventh nuclear test could be aimed at developing both high-yield and low-yield warhead designs. It's possible that several tests could be conducted simultaneously or quickly sequenced.

In terms of delivery platforms, the bulk of DPRK's ballistic missile inventory is comprised of short- and medium-range missiles, capable of striking South Korea, Japan, Guam and Hawaii.<sup>13)</sup> Test launches for these missile classes – and demonstration of the threat they pose to South Korea – precede the more recent flurry of North Korean missile tests. For example, the test of the KN-23 short-range ballistic missile (SRBM) in 2019 revealed an atypical flight path; on terminal approach

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10) ROK MND, *White Paper 2020*, 2020.

11) International Panel on Fissile Materials, *Global Fissile Material Report 2022*, July 2022, p. 62.

12) International Panel on Fissile Materials, *Global Fissile Material Report 2022*, July 2022, p. 63.

13) ROK MND (2020). Short-range and medium-range classes of DPRK missile forces are each believed to make up 45 percent of the total inventory. In other words, 90% of North Korean missiles can reach targets at short- or medium-range.

to its target, it conducted a “pull-up” maneuver in order to complicate the ability of ground-based interceptors. The KN-23 can strike any location on the Korean peninsula with either nuclear or conventional payloads.<sup>14)</sup>

A smaller fraction of the North Korean missile stockpile (10 percent) is believed capable of carrying a payload to intermediate, long, or intercontinental range.<sup>15)</sup> North Korea is currently trying to develop the Hwasong-17 to ensure the delivery of a bigger payload – potentially one capable of carrying multiple nuclear warheads to cause greater destruction anywhere in the U.S. – than earlier ICBMs, the Hwasong-14 and Hwasong-15.<sup>16)</sup> The ROK, Japan, and many U.S. bases in the Asia-Pacific are thus situated within range of North Korean nuclear-tipped missiles, but most of the continental United States (CONUS) remains out of reach of demonstrated North Korea delivery platforms.

North Korea also continues to increase the survivability of its missile force through investments in mobility, reliability, and diversity. The overall number of transporter erector launchers (TELs) has increased, with North Korea believed to possess as many as 100 TELs for short-range missiles, 50 for medium-range missiles, and 50 for ICBMs.<sup>17)</sup> In 2021, Pyongyang demonstrated a rail-mobile launch system, a platform that had faded from memory after Russia eliminated its rail-mobile SS-24 ICBM system under the START Treaty.<sup>18)</sup> Moreover, recent advances in North Korea's ballistic missile test program appear to be directed at developing capabilities to defeat or degrade the effectiveness of missile defenses deployed in the region, such as Patriot, Aegis Ballistic Missile Defense (BMD), and Terminal High Altitude Area

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14) Missile Defense Advocacy Alliance, “KN-23.” <https://missiledefenseadvocacy.org/missile-threat-and-proliferation/todays-missile-threat/north-korea/kn-23/>

15) ROK MND (2020).

16) Christy Lee, “Experts: North Korea Testing ‘Monster’ ICBM Designed to Attack US,” VOA News, November 09, 2022.

17) Narushige Michishita, “Strategic Implications of North Korea's Enhanced Nuclear and Missile Capabilities,” Society of Security and Diplomatic Policy Studies. <http://ssdpaki.la.coocan.jp/en/proposals/90.html>

18) “Rail-Mobile Launchers of ICBMs and their Missiles,” Fact Sheet, Bureau of Verification, Compliance, and Implementation, U.S. Department of State, August 2, 2010.

Defense (THAAD). In addition, North Korea's continued efforts with submarine-launched ballistic missile (SLBM) technology suggests an effort to counter land-based THAAD missile defenses by launching attacks from positions at sea outside the THAAD's radar field of view, although local Aegis BMD systems could likely still track these projectiles.<sup>19)</sup>

Whether and under what conditions Pyongyang could actually detonate nuclear weapons at range is unclear. North Korea has tried to miniaturize, lighten, and standardize its nuclear warhead for deployment on various missiles. In July 2017, a DIA assessment and some outside observers suggested North Korea had achieved the level of miniaturization required to fit a nuclear device on weapons ranging across the spectrum of its missiles, from SRBMs to intercontinental ballistic missiles (ICBMs).<sup>20)</sup> Though Kim Jong-un attested in January 2021 to the country's ability to "miniaturize, lighten and standardize nuclear weapons and to make them tactical ones," this technological achievement purportedly applies only to the short-range inventory. Uncertainty about the adequacy of the reentry vehicle for warheads atop medium- and long-range platforms remains high.<sup>21)</sup>

Despite much uncertainty about the effectiveness of North Korean nuclear and missile development, the pace and progress of these programs continues to challenge the ROK-US defense posture and broader alliance. If the near-unanimous interpretation of the North Korean regime's long-term intent for this capability – to hold regional *and* CONUS targets at risk, thereby enabling coercion of Washington into policy decisions or behavior beneficial to Pyongyang's interests – is correct, Pyongyang is close to achieving it. In other words, at the rate DPRK's missile program is advancing, the ability to threaten CONUS with a nuclear strike is a matter of "when," not "if." The increasing credibility of this threat continues to elicit concern in both Washington and Seoul about potential U.S. abandonment of its ally in the

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19) Ibid. For more detail on the status of the DPRK SLBM program, see

<https://www.38north.org/2022/09/sinpho-south-shipyard-activity-at-the-secure-boat-basin/>.

20) Mary Beth D. Nikitin, "North Korea's Nuclear Weapons and Missile Programs," *CRS In Focus*, Updated April 8, 2022.

21) Kristensen & Korda (2022).

event of a North Korean nuclear attack.<sup>22)</sup> Whether or not North Korean threats can “decouple” the ROK-US alliance in this way and dilute the salience of the U.S. security guarantee vis-à-vis the ROK persists as a topic of debate.<sup>23)</sup>

## 2) Intent

It is clear that North Korea's advancing nuclear and missile programs reflect deliberate commitment by the KJU regime to implementation of a series of a five-year Defense Development Programs. At the 8th Congress of the Workers' Party in 2021, it declared successful completion of the first five-year program and announced the start of its second consecutive five-year program. The plans emphasized, among other objectives, qualitative modernization and quantitative growth in the country's nuclear forces, as well as developmental programs such as hypersonic weapons, which have since been tested, multiple warhead-capable missiles and tactical nuclear weapons.<sup>24)</sup>

Less clear are the specific conditions under which the North Korean leadership would opt to employ its nuclear capability. Experts on North Korea's capabilities are split on whether the guiding doctrinal principle for the enhancements detailed above is assured retaliation or asymmetric escalation. The former concept focuses on a credible second-strike capability to deter an aggressor, while the latter emphasizes first use with the aim of sharply escalating, and subsequently ending, a conflict. Some, such as Bruce Bennet and Vipin Narang, see North Korea's nuclear strategy as predicated on threatening early nuclear use in a crisis.<sup>25)</sup> Indeed,

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22) Bruce W. Bennet et al., *Countering the Risks of North Korean Nuclear Weapons*, PEA1015-1, Santa Monica, CA: RAND, 2021.

23) For example, Mira Rapp-Hooper, “Decoupling is back in Asia: a 1960s playbook won’t solve these problems,” *War on the Rocks*, September 7, 2017; Kelsey Davenport and Julia Masterson, “Congressional Perspectives on U.S. Policy Toward North Korea and Denuclearization of the Korean Peninsula,” *An Arms Control Association Report*, August 2021.

24) Ankit Panda, “Sure, deter China—but manage risk with North Korea, too,” *Bulletin of the Atomic Scientists*, March 10, 2022.

25) Vipin Narang, “Why Kim Jong-un wouldn’t be irrational to use a nuclear bomb first,” *Washington Post*. September 8, 2017.

Pyongyang appears prepared to blur the line between conventional and nuclear use in ways that speak to an asymmetric deterrent strategy.<sup>26)</sup>

Others doubt that that Pyongyang could or would implement an asymmetric escalation strategy. For example, Lee and Alexandrova argue that North Korea has likely adopted an assured retaliation strategy because it is only viable and affordable option. This strategy requires a modest cost-effective nuclear arsenal, reduces Pyongyang's security dependence on Beijing, and permits politically safe centralized control over the nuclear weapons.<sup>27)</sup> The poor state of Pyongyang's nuclear command control and communications (NC3) system, strategic warning and intelligence, surveillance, and reconnaissance capabilities also undercut the credibility of its forces.<sup>28)</sup>

Another rationale for assured retaliation could stem from the sizable asymmetry in U.S. and DPRK nuclear forces, and implications therein for nuclear brinkmanship tactics. Should North Korea strike the ROK, there is a possibility that the Washington will respond in kind against North Korea because of its extended deterrence commitment to Seoul. In this manner, some observers (including senior-level participants in recent RAND wargames on DPRK nuclear-use scenarios) contend that North Korea would not use nuclear weapons early in a crisis or conflict because of the risk of a devastating response.

A third set of views on DPRK intent is that it depends, with North Korea possibly seeking assured retaliation in peacetime, and tactical advantage under conflict conditions.<sup>29)</sup> That is, North Korea aspires to achieve capabilities consistent with

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26) Ohn V. Parachini, Scott W. Harold, Gian Gentile, Derek Grossman, Leah Heejin Kim, Logan Ma, Michael Mazarr, and Linda Robinson. *North Korean Decision making: Economic Opening, Conventional Deterrence Breakdown, and Nuclear Use*, Santa Monica, CA: RAND, 2020.

27) Dong Sun Lee, Iordanka Alexandrova, "North Korean nuclear strategy: envisioning assured retaliation," *International Relations of the Asia-Pacific*, Volume 21, Issue 3 (September 2021), pp. 371-400.

28) Terence Roehrig, "The abilities—and limits—of North Korean early warning," *Bulletin of the Atomic Scientists*. November 27, 2017.

29) Anonymous, "What Is North Korea's Nuclear Strategy? A look at how Pyongyang views - and might use - its nuclear weapons," *Diplomat*, May 28, 2015.

both assured and asymmetric deterrence. This seems to adhere with the 2021 announcement at the 8th Party Congress that “the goal of advancing the nuclear preemptive and retaliatory strike capabilities was presented. The national defense force has risen to a level where it can preemptively suppress threats to hostile forces.”<sup>30)</sup>

However, a more recent public pronouncement of DPRK nuclear doctrine suggests the threshold for North Korea's employment of nuclear weapons may be falling. In September 2022, the Supreme People's Assembly passed a law authorizing its first use of nuclear weapons in five conditions of imminent threats against its leadership, national nuclear force command body or important strategic objects.<sup>31)</sup> This decision is believed to legitimize the use, at least from Pyongyang's perspective, of preemptive nuclear strikes against United States or South Korea should indicators of regime change be detected. Though there is speculation that the new policy is aimed at largely at coercion, it replaced a 2013 law that appeared at least nominally to prioritize deterring over defeating.<sup>32)</sup>

This shift in policy echoes other top-level statements suggesting that North Korea's nuclear capabilities are aimed at more than deterrence. KJU delivered a speech at a military parade in April 2022 that asserted the country's nuclear weapons “can never be confined to the single mission of war deterrence – which is the primary mission of their nuclear forces – when its “fundamental interests” are violated.<sup>33)</sup>

30) Translation from Sangkyu Lee, “Prospects for DPRK's Nuclear Use Scenarios and Deterrence Measures of the US and ROK Alliance,” *Journal for Peace and Nuclear Disarmament*, 5:sup1(2022), pp. 69-84.

31) Ellen Kim, “North Korea States It Will Never Give Up Nuclear Weapons,” CSIS, September 9, 2022.

32) Admittedly, the 2013 law “On Consolidating the Position of Nuclear Weapons State for Self-Defense,” also known as the Nuclearizations Law, was not taken at face value. Article 2 stipulates that nuclear weapons will serve to “deter and defeat aggression and attack of the enemy against our republic and to inflict an annihilating retaliatory strike on its home countries…” This commitment to a nuclear force capable of imposing immense destruction on states that undertake aggression against it suggests Pyongyang may not have ever limited the role of nuclear weapons to deterring and retaliating.

33) Sang-Hun Choe, “North Korea Holds Military Parade With Nuclear Threat,” *The New York Times*, April 26, 2022.

He added in that kind of situation, the country's nuclear forces would have to go ahead with their "secondary mission," which would be 'defeating' according to the 2013 law. This "secondary mission" had been previously articulated by KJU's sister, Yo-jung Kim, who argued that in the event of "military confrontation" by the ROK, "our nuclear combat forces (would be) inevitably obliged to carry out its (secondary) mission... (a) terrible attack would be mounted and the South Korean army would have no other choice but to suffer tragic lot of extermination."<sup>34</sup> This rhetoric suggests that the option of offensive nuclear use against South Korea is on the table for Pyongyang.

Public messaging aside, the ROK-US alliance should take the possibility of rational North Korean nuclear escalation seriously. For the KJU regime, the perceived benefits of employing nuclear weapons could outweigh the perceived risks or costs for a number of reasons. Keir Lieber and Daryl Press have argued that a "use or lose" incentive for nuclear use could follow rationally from fear-based desperation, a last-ditch effort to change the balance in a conflict.<sup>35</sup> The operational, maintenance, and logistics constraints North Korea would face during any sustained military campaign could also foster "use or lose" motivations, with great pressure to strike first and degrade adversary assets before those assets prohibitively reduce the DPRK's chances of retaliation.

Given the regime's singular focus on self-preservation, the most plausible rationale for DPRK nuclear use likely centers on preventing a crisis of regime change.<sup>36</sup> Indeed, since 2016, the ROK Ministry of National Defense (MND) has assumed that North Korea would not use nuclear weapons until the survival of the North Korean

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34) Christian Davies, "Kim Jong Un's sister condemns South Korean defence minister as a 'lunatic'," *Financial Times*, April 5, 2022.

35) Keir Lieber and Daryl Press, "The Next Korean War," *Foreign Affairs* online, April 1, 2013; Keir Lieber and Daryl Press, "Coercive Nuclear Campaigns in the 21st Century: Understanding Adversary Incentives and Options for Nuclear Escalation," *Report for the Project for Advanced Systems and Concepts for Countering Weapons of Mass Destruction*, Monterey, CA: Naval Postgraduate School, 2013.

36) North Korea may be exposed to the possibility of a regime collapse; it suffers from chronic economic difficulties and has maintained relatively low political stability due to its personalist dictatorship.

state and its political leadership is threatened during the course of war.<sup>37)</sup>

Another motivation for DPRK nuclear escalation could stem from a belief that employment of nuclear weapons could terminate a conflict quickly, on Pyongyang's terms. This perception was codified in the latest version of North Korea's nuclear policy, which writes, "in case the need for an operation to prevent an expansion and protraction of war, and taking an upper hand in a war, is inevitably raised at the time of contingency," the regime can use nuclear weapons.<sup>38)</sup> The underlying logic would be to limit the course of a war with an initial use of nuclear weapons and force ROK-US concessions with a threat of further escalation. As will be described below, Pyongyang's brinkmanship could be rooted in a gamble that the United States would not retaliate against North Korea, even for an attack on a U.S. ally, out of concern about a possible reaction by North Korea or, under certain conditions, the People's Republic of China.

## 2. Potential DPRK approaches to the employment of nuclear weapons

Premised on the above understanding of North Korean intent and capabilities, this section uses scenarios as a way to foster the development of ROK-US strategy for escalation risk.<sup>39)</sup> It walks through three types of situations where detonation of a North Korean nuclear weapon could take place: deliberate/intentional use, inadvertent/unintentional use as a result of accident or miscalculation, and contingencies involving China. All of these hypothetical situations would require an unfortunate overlap of enabling conditions to come to pass, some of which are unlikely in the current security environment. Digging further into the deterrence gaps that could lead to such events could drive greater alliance cohesion over responses to North Korea's nuclear threats.

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37) ROK-US actions in support of regime change could involve seizure of DPRK nuclear weapons, in which case the leadership may opt to make use of its nuclear capabilities before its control over those weapons is reduced.

38) Jeongmin Kim. "Full text: How North Korea transformed its nuclear doctrine law." *NK News*. September 9, 2022.

39) Michael Fitzsimmons, *Scenario Planning and Strategy in the Pentagon*, Washington D.C.: US Army War College Press, 2019.

### 1) Intentional use of nuclear weapons

In light of the risk of further escalation, deliberate employment of the North Korean nuclear capability would likely be backed by the regime's determination to wage all-out war, and that nuclear use could change a situation by shocking the ROK and the United States. The 2013 Nuclearization Law described three broad approaches to wartime employment of nuclear weapon, which align with the early, middle, and late stages of a conflict.

At the onset or triggering of a conflict, North Korea could seek to use nuclear weapons against military targets in the region with the goals of shocking the alliance and degrading its ability to sustain an invasion of its territory. By striking U.S. bases in Hawaii or Guam, North Korea may prevent the United States from sending its augmented force to South Korea. If the ROK-US alliance pauses to respond, North Korea might believe it could block international assistance and prevail on the Korean peninsula. Since Pyongyang would likely want to terminate the war as quickly as possible, it may opt for low-yield or tactical weapons, to minimize casualties while causing enough disarray in Seoul and Washington to lead them to back down.

A plausible North Korean objective for nuclear use in the middle of a war could be to change the course of conventional conflict in a way that is favorable to North Korea. To achieve such aims, Pyongyang could employ nuclear weapons against target's associated with the ROK military, such as command and control facilities, arsenals, airports, ports and bases. Such strikes would seek to decrease the morale and resolve of the ROK force; physically destroy ROK military capabilities; and prevent or delay the flow of additional U.S. forces onto the peninsula.

In the late stages of a conflict, if the ROK-US alliance is winning and North Korea is no longer able to fight and/or regime survival is at stake, North Korea could attempt to leverage nuclear weapons to terminate the war. Fear-based desperation might drive Pyongyang to a countervalue target, betting that the ROK-US alliance would want to make a negotiation that brings an end or ceasefire to the war.

These three employment concepts are encapsulated below in Table 1. In all of these situations, it is very unlikely that North Korea will use nuclear weapons against its citizens and within its territory. The contamination of the territory and damage to the people caused by radioactivity would take a fatal toll on the legitimacy of the postwar North Korean regime and its ability to rebuild after the war.

Stage	Purpose(s)	Target(s)
Early	<ul style="list-style-type: none"> <li>• Terminate the war early</li> <li>• Eliminate ROK-U.S. will to fight</li> <li>• Isolate South Korea</li> </ul>	<ul style="list-style-type: none"> <li>• US regional bases (e.g., Guam, Hawaii)</li> </ul>
Middle	<ul style="list-style-type: none"> <li>• Prevent or delay the increase of the US force on the peninsula</li> </ul>	<ul style="list-style-type: none"> <li>• Port or airport within South Korean that can be used for augmented force</li> </ul>
	<ul style="list-style-type: none"> <li>• Change the course of war in the midst of conventional war</li> </ul>	<ul style="list-style-type: none"> <li>• Counterforce target within South Korean territory (ex. ROK's command and control facilities, arsenals, airports, ports and bases)</li> </ul>
Late	<ul style="list-style-type: none"> <li>• Terminate the war</li> </ul>	<ul style="list-style-type: none"> <li>• Countervalue target within South Korean territory (e.g., Seoul, Busan, large industrial complexes)</li> </ul>

[Table 1] Possible aims and targets for North Korean nuclear use at different stages of war

In addition to nuclear strikes against ROK-US targets, it is worth pointing out that North Korea could also opt to execute an electromagnetic pulse (EMP) attack. If a low-yield nuclear weapon (e.g., several tens of kilotons) is detonated at an altitude off the coast of Kaesong or Wonsan, the EMP could conceivably reach the entire Korean Peninsula, paralyzing power grids and major infrastructure. In this way, North Korea could cause damage to electronic equipment of the Korean military and the private sector while minimizing the impact on China and Russia. This type of attack could have the benefit of shocking DPRK's adversaries but avoiding direct conflict; as a result Washington might react less aggressively since physical damage is likely to be low.

## 2) Inadvertent use of nuclear weapons

North Korea's local provocations inherently cast a nuclear shadow; thus there always a possibility that tensions could unintentionally escalate across the nuclear threshold. Many permutations of miscalculation – where behavior is driven by a misjudgment, usually of adversary intent or behavior – are possible. For example, nuclear escalation could derive from North Korea's erroneous reading of Washington-Seoul actions as leading indicators of preemptive nuclear use. Contrastingly, ROK-US overreaction to North Korea's local provocation, to prevent a recurrence, could also cause tensions to spiral.

The probability of nuclear use by misunderstanding is also affected by the prospective challenges of command and control (C2) associated with North Korea's nuclear forces, as its capabilities expand. For example, recent efforts to delegate nuclear capabilities and assign related tasks to frontline units will demand attendant changes to the storage management system for tactical nuclear weapons, which may increase safety-related vulnerabilities. Such structural changes to C2 arrangements introduce the chance that a missile will be launched based on judgment of a delegated crew, not by the national command authority.

Accidental nuclear use is another possibility. An unintended explosion could have several causes, such as factors internal to the North Korea's nuclear or missile programs (e.g., incomplete missile precision or system failure). The 2022 Nuclear Policy Law addresses the safety of its nuclear weapons, noting the risks associated with weapons, technology and equipment. To mitigate these risks Pyongyang is believed to adhere to regulations on storage and management, to performance evaluation processes, and to conform with administrative, technical, and legal procedures. The risk of accidental nuclear detonation is likely greatest, however, in the event of a ROK-US invasion. Should ROK-US forces attempt to secure these weapons, their lack of familiarity with North Korea's internal safety measures raises the chance that these measures could be overwhelmed, driving an accident to occur.

factors	situation
Pre-war nuclear explosion	<ul style="list-style-type: none"> <li>• an unauthorized nuclear explosion, explosion accident</li> </ul>
False alarm	<ul style="list-style-type: none"> <li>• Human errors, such as test-firing, cyber terrorism, and mutual misunderstanding/misperception</li> </ul>
	<ul style="list-style-type: none"> <li>• Systematic errors such as technical faults, system failures</li> </ul>

[Table 2] Inadvertent use of nuclear weapons

### 3) Contingencies involving China

A third set of scenarios that could conceivably increase the risk of nuclear escalation by the DPRK relate to intent and capabilities of China, the North's ally and a peer competitor of the United States. Given the importance of stability on the peninsula to Beijing's security calculus, China will be involved in an escalating contingency on or near the Peninsula in one way or another. Beijing and Pyongyang share an interest in preventing an augmented U.S. presence in the region; the notion that tensions between the North and South could drive additional U.S. deployments is equally intolerable for both states.

A sudden change in North Korea is a well-known potential trigger for Chinese intervention. Indeed, it is widely if unofficially recognized that China is preparing for such an event. In 2004, the existence of the so-called "chick plan" was confirmed by a U.S. report quoted a Chinese military official description of preparations for such a mission.<sup>40)</sup> Though the KJU regime's solidification of control has since lessened the urgency of such plans, the nuclear shadow cast by PRC and DPRK capabilities over such a contingency continues to expand.

Another related pathway for Chinese intervention, against the backdrop of a collapsing DPRK regime, could originate in a determination by Beijing that North Korea's nuclear facilities are vulnerable and must be defended, if only to prevent

40) Thomas Woodrow, "The PLA and Cross-Border Contingencies in North Korea and Burma," In Andrew Scobell, Arthur S. Ding, Phillip C. Saunders, and Scott W. Harold ed., *The People's Liberation Army and Contingency Planning in China*, Washington, D.C: National Defense University Press, 2015, p. 209.

a ripple effect on Chinese territory. After entering North Korea about 200 kilometers from the border and forming a buffer zone, Beijing could deploy units to secure nuclear, chemical and missile-related facilities. This operation could alternatively involve North Korea's northeastern port, which China frequently uses.

To be clear, China's role in the above contingencies would not necessarily involve its nuclear forces. This could change, however, if ROK-US efforts to achieve alliance objectives in light of a deterrence failure – in the form of deliberate DPRK nuclear use -- involve employment of U.S. nuclear weapons. In this case, it is conceivable that China may opt to leverage its own nuclear threats, in an effort to come to the aid of its ally, perhaps as a way to deescalate hostilities.

A final group of pathways for North Korean nuclear threats or nuclear use relates to ongoing efforts by the United States to grapple with how best to deter two adversaries simultaneously.<sup>41)</sup> This set of contingencies is premised on Pyongyang's perceptions of how Chinese capabilities and behavior would shape the U.S. calculus vis-à-vis the peninsula. Given the “ironclad” nature of the ROK-US alliance and the U.S. commitment to extend deterrence to South Korea, Pyongyang may believe the only situation where nuclear use against the ROK would *not* guarantee a response in-kind would be when the United States is already preoccupied with another war involving China. In other words, Pyongyang might believe Washington would hesitate to retaliate against North Korea because a separate conflict has diminished its capability and will.<sup>42)</sup> According to this logic, the United States would effectively yield its position on the Peninsula to shore up its advantage in other regions.

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41) The debate surrounding the deterrence requirements of “three party dynamics” tends to focus on a trilateral dilemma involving the United States, China, and Russia, but a version of this problem also exists for the United States, China, and North Korea.

42) The form of U.S. counterattack in any situation will be the product of many factors, including capability, resolve, and the health of the ROK-US alliance. In the case discussed here, certain trends could dilute all three factors. The credibility of U.S. capabilities could be hampered by China's nuclear buildup and broader influence in the region, and US resolve could be exhausted from another or recent conflict. The health of all alliances can also change over time.

For example, North Korea could view a prolonged U.S.-China war over Taiwan as a window of opportunity to achieve its own strategic interests. It is not difficult to see how a drawn-out conflict in which China's attempt to invade is complicated by a resisting Taiwan and the development of the U.S. military against it could consume the focus of both capitals. In such a case, should a DPRK-ROK skirmish begin to spiral, the United States and China may pause to react. Pyongyang could threaten to use nuclear weapons to unless the United States withdraws all troops from South Korea or recognizes it as a nuclear state and lifts all sanctions. If China is losing the conflict, some believe Beijing might even endorse (or at least allow) North Korea's plan.

### III. Posture of the ROK-US alliance for the risk of nuclear escalation

#### 1. Past Policies

By strengthening its own capabilities and posture, the ROK military has enhanced the alliance's combined capabilities and overall posture for effectively deterring and responding to North Korea's nuclear and missile threats.<sup>43)</sup> The first bilateral strategy against North Korean threats of nuclear weapons and other weapons of mass destruction, "Tailored Deterrence Strategy (TDS)," was announced in 2013 at the 45th Security Consultative Meeting (SCM), the ministerial-level meeting for the military alliance. The strategy is underpinned by the U.S. commitment to provide and strengthen deterrence for South Korea "using full range of military capabilities, including the U.S. nuclear umbrella, conventional strike, and missile defense capabilities."<sup>44)</sup> Seoul has also committed to continue building reliable interoperable response capabilities and to develop the Korean Air and Missile Defense system (KAMD).

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43) Sangkyu Lee (2022).

44) Karen Parrish, American Forces Press Service. (2013). "U.S., South Korea Announce 'Tailored Deterrence' Strategy." USFK. October, 3.  
<https://www.usfk.mil/Media/Newsroom/News/Article/600966/us-south-korea-announce-tailored-deterrence-strategy/>

The TDS focuses primarily on general deterrence, but also covers response should Pyongyang actually use nuclear weapons. Furthermore, while the strategy speaks to non-military countermeasures in the diplomatic, information, and economic (DIE) domains, it has heavily placed military at its core. As of September 2022, the ROK and the United States have started to revise the 2013 TDS in order to integrate non-military instruments of national power of both allies and to address the operationalization of US extended deterrence in the event of North Korean nuclear use. The ROK Defense Minister recently confirmed the alliance will produce specific response measures for various scenarios involving nuclear threats from the North.<sup>45)</sup>

Since 2016, ROK implementation of the TDS has centered on development of the “Triad System,” comprised of KAMD and two striking systems: the Kill Chain and Korea Massive Punishment and Retaliation (KMPR). The Kill Chain was aimed at disablement of the DPRK’s nuclear and missile operations systems, including its missiles, mobile missile launchers, command and control systems, and relevant fixed installations. The KMPR concept emphasized the direct targeting of DPRK leadership, including its war headquarters, through deployment of missiles capable of simultaneous, massive-scale precision strikes, and special operations units.<sup>46)</sup>

In 2018, the ROK armed forces renamed the Triad system as the “WMD Response System,” composed of KAMD and the “Strategic Strike System,” which incorporated the Kill Chain and KMPR. This name change was aimed at muting the reference to specific targets as part of a broader interest within the Moon Administration to reduce tensions on the peninsula. The main features of the Strategic Strike System are long-distance surveillance capabilities and precision strike capabilities.<sup>47)</sup> It seeks to “deter by denial” as well as “deter by punishment”, and to counter a full range of asymmetric threats.<sup>48)</sup>

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45) KBS. “Defense Chief: S. Korea, US Revising Tailored Deterrence Strategy.” KBS World, September 15, 2022.

46) For a discussion of the escalation risks some see as inherent in these systems, see Ankit Panda, “South Korea’s Decapitation Strategy has More Risks than Benefits,” Commentary, Carnegie Endowment for International Peace, August 15, 2022.

47) Lee (2022).

48) Glenn H Snyder, “Deterrence and Power,” *Journal of Conflict Resolution*, Vol. 4, No. 2(1960), pp. 163-178.

## 2. ROK perspective of the risk of DPRK nuclear escalation and deterrence of such risk

Since the 8<sup>th</sup> Party Congress when the DPRK declared its development of tactical nuclear weapons, some of the ROK government and policy analysts have increased their doubts on whether the U.S. extended deterrence is still credible and responsive to such threats. In the past, the DPRK had pursued its nuclear weapons such as ICBM targeting the U.S. mainland, which will be never used but strategically deter augmented forces from entering Korean peninsula. Pyongyang's tactical nuclear weapons or other marginal nuclear options such as nuclear EMP attacks increase possibility in which Seoul can be attacked by nuclear bombs before the U.S. starts to react. In case that DPRK threatens to set for example New York as the next target, the U.S. presidents on the behalf of American tax payers is not likely to be prompt to make a decision to retaliate. This is so called decoupling problem, which is a total failure of the U.S. extended deterrence. That can't happen if all players make a rational choice. What some of the ROK government officials and experts are afraid is a situation that they do not.

There is a possibility that the DPRK leader lacks expected rationality or faces a circumstance that compels his irrational choice to make a nuclear strike. If DPRK leader is a rational actor, it is very unlikely to use nuclear weapons against the ROK-US alliance, since he will be feared that the possibility of his regime's end would become a reality as the 2022 U.S. Nuclear Posture Review declares. It says there is no scenario in which the Kim regime could employ nuclear weapons and survive.<sup>49)</sup> The U.S. has more than 5,000 nuclear weapons and it has various options to deter North Korea. Anthony Cotton, as the nominee of the U.S. strategic commander witnessed that the U.S. current Ground Based Interceptors (GBI) fleet has the capability to defend the U.S. from a limited threat from North Korea and other rogue nations.<sup>50)</sup>

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49) DoD, 2022 Nuclear Posture Review, October 27, 2022, p. 12.

50) US Committee on Armed Services, "Nomination - Cotton," September 15, 2022, [https://www.armed-services.senate.gov/hearings/nomination\\_-cotton](https://www.armed-services.senate.gov/hearings/nomination_-cotton)

The decoupling problem is especially distressing in the Moon-Trump administrations that experienced a political divergence between the allies. Donald J. Trump, the 45<sup>th</sup> U.S. president, had a distrust in the ROK-US alliance and basically sent a political signal that the U.S. may not want to be intertwined with the ROK fate. The ROK is concerned that the U.S. president is the sole person who has the right of final decision to make a nuclear strike, although Washington security establishment wants to secure the U.S. commitment to extended deterrence which is the cornerstone of its alliance network around the world. If Donald J. Trump again or another anti-alliance candidate becomes the 47<sup>th</sup> U.S. president, the U.S. commitment to extended deterrence to more than thirty countries might be reviewed.<sup>51)</sup> In a Pew Research Center's survey, 46% of U.S. adults say "we should pay less attention to problems overseas and concentrate more on problems here at home."<sup>52)</sup>

Recently, skepticism toward U.S. extended deterrence to the ROK has raised the concern that Seoul may choose to go nuclear.<sup>53)</sup> With North Korea's nuclear capability to reach U.S. territory, most South Korean and American experts have questioned if the United States would actually provide nuclear retaliation against the North should South Korea be attacked by North Korea's tactical nuclear weapons.<sup>54)</sup> Recent several polls show that South Koreans increasingly support developing an indigenous nuclear capability. According to various polls conducted in 2021 and 2022, more than 70% of South Koreans – 74.9%, according to the SAND research institute's figures released last June – support the country's indigenous nuclearization out of the fear of North Korean nuclear bombs.<sup>55)</sup> While their opinion seems grounded on anxiety rather than on strategic considerations, it has generated a number of policy debates among experts whether nuclear arming can be a viable

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51) David J. Trachtenberg, "US extended deterrence: how much strategic force is too little?," *Strategic Studies Quarterly*, Vol. 6, No. 2(Summer 2012), p. 68.

52) <https://www.pewresearch.org/politics/2019/12/17/6-views-of-foreign-policy/>

53) Lami Kim, "South Korea's Nuclear Hedging?," *The Washington Quarterly*, 41:1(2018): 115-133.

54) Seong-Chang Cheong, "The Case for South Korea to Go Nuclear: It may be the best option for the South Korea-U.S. alliance to deter a nuclear war with North Korea," *The Diplomat*, Oct 27, 2022.

55) Ibid.

option considering risks that will bring to the ROK security.

Yet, it is not an option that the current Yoon Administration would be willing to choose. The Yoon administration believes in alliance and the U.S. extended deterrence will be more effective to deter potential nuclear attacks. In his policy list, No. 105 is Strengthening ROK-US Military Alliance and Expanding Defense Science and Technology Cooperation. Its goals and main contents related to deterrence against North Korea are as follows:

### Goals

- Strengthen execution capability of the ROK-US extended deterrence and establish robust combined defense posture
- Enhance trust between the alliance and strengthen solidarity of the alliance by expanding security cooperation among ROK, US, and Japan

### Main Contents

- (Enhancing execution capability of extended deterrence) Reactivate ROK-US Extended Deterrence Strategy and Consultation Group (EDSCG), establish ROK-US cooperative system for deployment of strategic assets and strengthen regular exercises
- (Building combined defense posture) Change the name of the ROK-US theater-level combined exercise (CPX), integrate combined and government exercises from the second half of year 2022, and resume combined field training exercise (FTX)
- (Expanding ROK-US-Japan security cooperation) Step-by-step expansion of ROK-US-Japan Security Cooperation by strengthening various ROK-Japan and ROK-US-Japan communications and facilitating policy-strategic level consultations

This policy is expected to strengthen solidarity of the ROK-US military alliance and establish foundation for development toward global alliance. Moreover, the ROK's new government has reinvigorated its grip on the ROK's own deterrence capabilities. Since the beginning of the Yoon Administration in May 2022, Seoul has reinvigorated its military posture for preemptive and retaliatory strikes against the DPRK's strategic assets and its leadership by developing concepts of Kill Chain and KMPR, respectively. Also, it plans to establish a "strategic command" to serve as an overarching organization, and to implement the three-axis counter to North Korea's evolving nuclear and missile threats.

### **3. US perspective on the risk of DPRK nuclear escalation and deterrence of such risk**

Public messaging behavior makes clear that entities at the highest levels and front lines of the U.S. government are tracking the significance of the threat posed by North Korea's expanding set of nuclear options to the ROK-US defense posture, both on and off the Korean peninsula. Top U.S. officials routinely articulate the U.S. commitment to addressing this risk with their South Korean counterparts, with the most Joint Statement noting the "two Presidents share the view that the DPRK's nuclear program presents a grave threat not only to peace and stability on the Korean Peninsula but also the rest of Asia and the world."<sup>56</sup> Statements from functional and regional Combatant Commanders most relevant to the North Korean problem set attest to the joint force's readiness and resoluteness in the face of the threat of nuclear escalation, however it may evolve. Take, for example, the Commander of US Forces Korea:

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56) "United States-Republic of Korea Leaders' Joint Statement," White House Pressroom, May 21, 2022. For a defense ministerial statement, see "Secretary of Defense Lloyd J. Austin III Remarks Welcoming the Republic of Korea's Minister of National Defense, Lee Jong-Sup, to the Pentagon," US DoD, July 29, 2022. For a foreign ministerial statement, see "Secretary Blinken's Call with Republic of Korea Foreign Minister Park," Office of the Spokesperson, Department of State, August 19, 2022.

“North Korea's WMD program, asymmetric capabilities (to include cyber capabilities), and sizeable conventional military force remains a significant threat to South Korea, US and Allied forces in both South Korea and the region as well as the United States. These standing tensions require a combat credible force consisting of a strong, professionally trained, and equipped US–ROK Alliance to deter threats and to sustain peace and stability on the Korean Peninsula...”<sup>57)</sup>

The United States also appears to anticipate that the risk of North Korean nuclear escalation will wax and wane. The intelligence community's most recent annual threat assessment expects Pyongyang to “vacillat(e) between periods of escalatory behavior and symbolic gestures toward the South to exploit differences between Washington's and Seoul's approach to solving the Korea problem.”<sup>58)</sup> Nuclear threats are perceived as integral to this deliberate program, with the KJU regime expected to “periodically ... us(e) aggressive and potentially destabilizing actions to reshape the regional security environment ... (to) include developing and demonstrating capabilities up to and possibly including the resumption of nuclear weapons and ICBM testing.”<sup>59)</sup>

Washington's key challenge is thus how to affect periods of instability in a manner that both assures Seoul of its security guarantee *and* deters possible or further nuclear escalation by Pyongyang. To achieve this objective, the United States has committed to using “all available levers – including diplomatic, informational, military, and economic tools” as well as the “full range of its military capabilities, including nuclear, conventional, missile defense, and other advanced non-nuclear

57) “Statement of General Paul J. LaCamera Commander, United States Command; Commander, United States–Republic of Korea Combined Forces Command; and Commander, United States Forces Korea Before the House Committee on Appropriations Subcommittee on Defense, Fiscal Year 2023 at <https://docs.house.gov/meetings/AP/AP02/20220517/114752/HHRG-117-AP02-Wstate-LaCameraP-20220517.pdf>. See also DoD, “Admiral Charles A. Richard, Commander, U.S. Strategic Command, Holds a Press Briefing,” April 22, 2021.

58) The Office of the Director of National Intelligence (ODNI), 2022 Annual Threat Assessment of the U.S. Intelligence Community, March 8, 2022.

59) Ibid.

capabilities.”<sup>60</sup>) In practice this pledge take a variety of forms; for the purpose of evaluating deterrence of DPRK nuclear use, this paper will focus on a subset of these mechanisms that are central to the U.S. ability and intent to extend *nuclear* deterrence to the ROK.

The backstop of the U.S. commitment to South Korea is the strategic nuclear triad, composed of ballistic missile submarines (SSBNs) armed with SLBMs, land-based ICBMs, and nuclear-capable heavy bomber aircraft capable of delivering gravity bombs and cruise missiles.<sup>61)·62)</sup> These forces are arrayed -- geographically dispersed and deployed at varying levels of alert – to both complicate Pyongyang’s calculus and to provide the flexibility required to execute a strategy of deterrence tailored to the DPRK nuclear and missile threat.<sup>63)</sup> This flexibility manifests in a wide portfolio of operational approaches, to include nuclear and non-nuclear options, immediate or delayed-response options; an array of nuclear strike options, in terms of scale, yield and delivery mechanisms; and the option to use nuclear weapons first, or after a nuclear weapon is confirmed to be inbound, or has already been employed and detonated on U.S. or allied soil.<sup>64)</sup>

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60) “Joint Statement on the Extended Deterrence Strategy and Consultation Group Meeting,” US DoD, September 16, 2022.

61) DoD, “Fact Sheet: 2022 Nuclear Posture Review and Missile Defense Review,” at <https://media.defense.gov/2022/Mar/29/2002965339/-1/-1/1/FACT-SHEET-2022-NUCLEAR-POSTURE-REVIEW-AND-MISSILE-DEFENSE-REVIEW.PDF>; “The Importance of the Nuclear Triad,” at <https://media.defense.gov/2020/Nov/24/2002541293/-1/-1/1/FACTSHEET-THE-IMPORTANCE-OF-MODERNIZING-THE-NUCLEAR-TRIAD.PDF>; The office of the Deputy Assistant Secretary of Defense for Nuclear Matters, *Nuclear Matters Handbook 2020 [revised]* at <https://www.acq.osd.mil/ncbdp/nm//NMHB2020rev/chapters/chapter3.html>.

62) The size and structure of the U.S strategic nuclear triad is largely shaped by the New Strategic Arms Reduction Treaty (New START), which caps the total number of deployed launchers at 700, the total number of deployed and nondeployed launchers at 800, and the total number of deployed warheads at 1550. The most recent U.S. articulation of New START force levels declared 686 deployed launchers, 800 deployed and non-deployed launchers, and 1515 deployed warheads. <https://www.state.gov/new-start-treaty-aggregate-numbers-of-strategic-offensive-arms-of-the-united-states-and-the-russian-federation-february-2011-march-2022/>

63) William A. Chambers, Caroline R. Milne, Rhiannon T. Hutton, and Heather W. Williams, “No-First Use of Nuclear Weapons: A Policy Assessment,” IDA document: P-20513, January, 2021.

64) *Ibid.*

Confidence in the reliability and speed of the process by which the United States could utilize such options to affect the types of scenarios outlined above varies from high to moderate. There is little doubt that overall, U.S. nuclear forces are capable and ready; in other words, the Commander of U.S. Strategic Command's assessment that "we're very familiar with North Korea's capabilities and I'm very confident in our ability to deter that" is trusted.<sup>65)</sup> However, questions about the extent to which the triad's suite of capabilities – and the attributes those capabilities possess – can counterbalance the different ways the evolving DPRK threat could manifest persist.<sup>66)</sup> For example, whether the geographic distance between the launch locations of U.S. ICBM's or SLBM's and the peninsula would adversely impact the ROK-US decision-making timeline is unclear.

Evolution in the U.S. stockpile of "tactical" or non-strategic nuclear weapons (NSNWs) has also highlighted concerns about the sufficiency of the extended deterrence architecture in the Asia-Pacific, especially when compared to the regional posture the United States maintains with its North Atlantic Treaty Organization (NATO) allies in Europe. Such concerns date back to the early 1990s, when all NSNWs were withdrawn from the Peninsula as part of the Presidential Nuclear Initiatives.<sup>67)</sup> The pool of regional NSNW assets was further winnowed in 2010 with the retirement of the Navy's nuclear cruise missile, the Tomahawk Land Attack Missile.<sup>68)</sup> The commitment by the 2018 Nuclear Posture Review to the development of a nuclear-tipped sea-launched cruise missile (SLCM-N) was seen

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65) "Admiral Charles A. Richard, Commander, U.S. Strategic Command, Holds a Press Briefing." US DoD, April 22, 2021.

66) Kelsey Davenport with Julia Masterson, "Congressional Perspectives on U.S. Policy Toward North Korea and Denuclearization of the Korean Peninsula," An Arms Control Association Report, August 2022.

67) Susan J. Koch, "The Presidential Nuclear Initiatives of 1991–1992," Center for the Study of Weapons of Mass Destruction Case Study 5, National Defense University, September 2012; Eli Corin, "Presidential Nuclear Initiatives: An Alternative Paradigm for Arms Control," NTI Report, February 29, 2004.

68) James M. Action, "Extended Deterrence and Communicating Resolve," *Strategic Insights*, Volume VIII, Issue 5 (December 2009, Carnegie Endowment for International Peace; Admiral Sandy Winnefeld and James N. Miller, "Bring Back the Nuclear Tomahawks," *Proceedings* (US Naval Institute), Vol. 143/5/1,371 (May 2017).

as reviving U.S. priority on its deterrence posture in Northeast Asia.<sup>69)</sup> However, the FY2023 budget request – and its elimination of SLCM-N funding -- has complicated the future of that system.<sup>70)</sup> For those that look to “hard power” indicators of resolve, the (continued) lack of a permanent, nuclear-capable presence or nuclear-sharing arrangement in the region raises doubt about the credibility of U.S. extended deterrence.<sup>71)</sup>

That being said, Washington has been making a concerted effort to partner with the ROK to allay doubts about the U.S. willingness to intervene in a nuclear crisis or conflict, especially for those concerns rooted in uncertainty over precisely *how* the United States intends to intervene. While bolstered ROK-US relations have driven working-level momentum across a variety of issue areas, there are three specific lines of effort that stand to institutionalize assurance of the ROK by “elevat(ing) Seoul’s role in U.S. nuclear decisions intended to protect South Korea”:<sup>72)</sup>

- *Resumption of the Extended Deterrence Strategy and Consultation Group (EDSCG)*<sup>73)</sup>  
In September 2022, this peacetime consultative mechanism convened a group of ROK-US senior leaders for the first time since 2016 to discuss extended deterrence measures against North Korea. To ensure the EDSCG forum provides the requisite value added, an expert-level session is planned for the first half of 2023, with meetings at the Under Secretary and Vice Minister level expected to occur annually.<sup>74)</sup>

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69) Masashi Maurano, “What the New US Nuclear Posture Means for Northeast Asia,” *The Diplomat*, August 29, 2018.

70) “Nuclear-Armed Sea-Launched Cruise Missile (SLCM-N),” CRS In Focus, April 25, 2022. Lawrence Ukenye and Connor O’Brien, “Congress poised to shoot down Biden’s nuclear rollback,” July 6, 2022; Kevin Knodell, “Congress quietly debates new sea-based nuclear weapons amid China tensions,” *Stars and Stripes*, September 6, 2022.

71) Daryl G. Press, *Calculating Credibility: How Leaders Assess Military Threats*, Ithaca: Cornell University Press, 2005.

72) “Strengthening the Ironclad U.S.-ROK Alliance,” Office of the Spokesperson, Department of State, March 17, 2021; Gabriel Dominguez, “Seoul pins hope on U.S. strategic assets to deter Pyongyang,” *Japan Times*, June 8, 2022.

73) “Joint Statement on the Extended Deterrence Strategy and Consultation Group Meeting,” US DoD, September 22, 2016.

74) “Opening Statement at the U.S.-ROK Extended Deterrence Strategy and Consultation Group,” US Mission Korea, September 16, 2022.

- *Ongoing rewrite of joint wartime contingency plans.*<sup>75)</sup> Ministerial-level approval of the Strategic Planning Guidance in late 2021 gave the ROK military and the Future Combined Forces Command the ability and authority to update ROK-US operational plans so that they can more effectively account for recent advancements in the North Korean nuclear and missile threat.<sup>76)</sup>
- *Resumption of large-scale combined military exercises.* Joint training events comprise another set of ROK-US activities that are being ramped up after a period of dormancy.<sup>77)</sup> In addition to redressing any degradation to allied deterrence and defense capabilities, combined exercises provide the critical (only?) way for locking in the “clear advance coordination between the ROK and US (that) would be vital to moving quickly” in a regional crisis.<sup>78)</sup>

#### IV. Recommendations for Sharpening the ROK–US Deterrence Posture

For the foreseeable future, even as the ROK-US posture is being re-strengthened, the coercive bargaining leverage resident in North Korea's nuclear program will remain a challenge. The key will be ensuring that implementation of revived consultations, exercises, and coordinated planning efforts tie specifically to the DPRK nuclear threat, and deterrence gaps surrounding that threat, without incurring additional risk.<sup>79)</sup>

75) DoD, “53rd Security Consultative Meeting Joint Communiqué” December 2, 2021; Office of the Chairman of the Joint Chiefs of Staff Public Affairs, “Readout of Chairman of the Joint Chiefs of Staff Gen. Mark A. Milley’s Meeting with Chairman of the Republic of Korea Joint Chiefs of Staff Gen. Won In Choul,” Joint Chiefs of Staff, March 30, 2022.

76) Sukjoon Yoon and Yongweon Yu, “How Will South Korea and the US Rewrite Their Operational Plan?,” *The Diplomat*, December 22, 2021.

77) United States Committee on Armed Services, “Statement of General Robert B. Abrams Commander, United Nations Command; Commander, United States–Republic of Korea Combined Forces Command; and Commander, United States Forces Korea Before the Senate Armed Services Committee,” February 12, 2019.

78) Markus V. Garlauskas, Ken E. Gause, Elizabeth Yang, “North Korea's Arena of Asymmetric Advantage: why we should prepare for a crisis in the yellow sea,” October, 1, 2021.

79) Ankit Panda, “South Korea’s “Decapitation” Strategy Against North Korea Has More Risks Than Benefits.”

We recommend focusing on working-level steps to posture existing/nascent extended deterrence initiatives for success. These relationships matter most for providing continuity in alliance posture and policy.

1. *Ensure EDSCG provides requisite utility.* Conduct workshops among action officers focused on scenarios such as those introduced above.
2. *Further strengthen the Alliance's information sharing, and consultation process, as well as joint planning and execution.* Upgrade its deterrence strategy tailored to deter and respond to DPRK's advancing nuclear and missile threats.
3. *Initiate a concepts and doctrine exploration/development process at the strategic/operational level, perhaps in the form of exchanges among war colleges.* This would aim to provide a forum in which thinking about how to deter (and how to fail to deter!) can be shared among allies. If possible, include aspects of the planning process.
4. *Explore a trilateral or quadrilateral form of information sharing and planning with Japan (and Australia).* The 2022 Nuclear Posture Review notes that this is an important goal to identify opportunities for these multilateral forms. Based on its experience in Europe, the U.S. should take the lead to strengthen its alliance network on nuclear issues against China as well as DPRK.

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## **Changes in International Environment and the Development of ROK-U.S. Defense Space Force**

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## I. Introduction<sup>1)</sup>

Future warfare has different characteristics from conventional warfare. In particular, as a decisive factor in future warfare, the United States during the Biden administration has proposed “Decision-Centric Warfare”, which is a concept that secures an edge through quick decisions based on information superiority. The key element of information superiority is to collect information through satellites and to secure communication network. As countries intensify competition for this goal, space threats become greater as they have the abilities to attack adversaries’ space assets and protect their own space assets. At this juncture, this research strives for drawing lessons by analyzing the case of the United States, which is at the forefront of defense and space power and, through this, presenting the direction of South Korea’s defense and space power development.

As space threats are intensified, it is time to study on ways to strengthen defense space force for security. Here, defense space force includes not only space force such as satellites and launch vehicles, but also space-related personnel, systems, and organizations in terms of policies, doctrines, and operations to utilize them. Through the case analysis of the United States and that of South Korea today, this research presents the direction of South Korea’s defense space force development suitable for the current situation of South Korea. More concretely, this research analyzes the current U.S. defense space force-related systems, policies, and strategies and, based on this analysis, to find an appropriate strategy suitable for the South Korean situation.

Most existing studies on space focus on technological development and industrial promotion policies. In some studies on defense space force, there are comparative studies on defense space organizations, but studies on organizations and policies suitable for South Korea’s situation are in short supply. This research is distinctive from previous studies on space because it deals with not space industry or technology but defense space force. Specifically, it analyzes defense space force-related policies from an integrated point of view of for its development.

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1) This chapter was written with reference to part of Lee, Su-Mi. 2021. “South Korea’s Space Program and Its Implication,” *The Korean Journal of Security Affairs*, Vol. 26, no. 2, pp. 69-88.

## II. Global security environment and space development

From the perspective of realists, a state's capability predicts its behavior more accurately than its intent does because no one can be sure of a state's goal (International Relations 2006, 231; Mearsheimer 2007, 73). States may conceal their genuine intentions behind their policy for a variety of reasons. Because their goals do not always translate into the anticipated policy or outcome, even if there were a mechanism to obtain their intents, doing so would not provide consequential knowledge (Morgenthau 1978). As a result, to predict the actions of other states, one must “always assume the worst” regarding the intentions of foreign states and evaluate their capacities while simultaneously fighting with them for power in order to ensure its survival (Mearsheimer 2007, 75). This captures the tragedy of great power politics in its purest form.

Because most space technology has a dual purpose, the tragedy of great power politics is even worse in this field. The security conundrum is made worse by the difficulties of separating offensive weapons from defensive ones, and competitiveness among spacefaring states is heightened by the dual-use nature of space technology.

The status quo in Asia as well as in the world has been destabilized as a result of China's growing influence in a variety of fields, including the economic, military, and space, with its once cooperative relations with the United States become competitive ones. Territorial disputes in the South and East China Seas; Chinese cyberattacks to undermine the US and other liberal democracies; authoritarian attempts to suppress dissent in Hong Kong or to brutally repress the ethnic and religious identities of local communities in Xinjiang and Tibet; and competition for dominance in the high technology sector and in space exploration are just a few of the issues that have caused tensions between the US and China (Nilsson-Wright and Jie 2021, 3; Martin 2021).

In the area of space, the United States had prevented China from participating in the ISS project, so there was already a lot of friction between the two countries. China's animosity toward the United States increased when the United States passed

the Department of Defense and Full-Year Continuing Appropriations Act of 2011, which forbade NASA from utilizing any funds for programs involving China. Some claim that the creation of the U.S. Space Forces as one of the six branches of the U.S. Military under the U.S. Air Force created a space race akin to the Cold War between the United States and China (Markovich, Chatzky, and Siripurapu 2020).

China has extensive space capabilities with cyber, and co-orbital satellite systems, directed energy, direct ascent kinetic kill vehicles (KKVs), electronic warfare, making it the second-largest satellite-producing nation in the world. Beijing's principal motivation for developing its space programs and operations appears to be national security, despite the fact that it appears to anticipate that doing so will help it increase its political, economic, and military dominance. Washington paid attention to such a mark. ASAT (Anti-Satellite Weapons) technology that China is currently developing and improving has the potential to destroy space objects in low and high orbit, according to a report from the U.S. Department of Defense released on September 1, 2020 (Erwin 2020).

As the United States extensively relies on space technology for its military operations, Washington is compelled to assume the worst about China's intentions behind its endeavor to improve the ASAT technology and consider it a threat to U.S. space assets as well as its military efficacy. Although China may explain its development or upgrading of the ASAT technology by claiming that it would be used to remove its retired satellites or to defend its assets in space, Washington is forced to presume that China's claim is false (Stokes, Alvarado, Weinstein, and Easton 2020). Washington's military prowess and effectiveness on Earth would be seriously weakened if it failed to preserve its superiority in space technology and capabilities (Lee 2021, 78).

Former U.S. Vice President Mike Pence explicitly voiced Washington's concern when he said that a new space race between the US and China is underway, with much bigger stakes than the one between the US and the Soviet Union, and that China aspires to take control of the strategic high ground on the moon and establish itself as the leading space power (Davenport, 2019). The International Lunar Research

Station, which China announced it will work on for the first time with Russia, increased the stakes and strained relations between the United States and China.

China appears to be aiming to set up international space governance with support from developing countries by asserting its leadership, establishing new norms and principles, and ultimately reshaping the global order by emphasizing that the International Lunar Research Station will be accessible to any interested countries (Nilsson-Wright and Jie 2021, 3). The United States would therefore not be overreacting if it believed China to be a revisionist force that is opposed to American principles and interests. Washington's position as a hegemon has been questioned and damaged as US-China ties become increasingly competitive. This condition of affairs seemed to compel Washington to mobilize its friends against Beijing by enlarging and redefining the reach of its alliance with its partners (Martin 2021).

For many years, South Korea and the United States have regarded one another as allies. The ROK-US alliance was established after the Mutual Defense Treaty was signed in 1953 by the two nations. Military cooperation between the two nations has remained unwavering despite the fact that the end of the Cold War's altered the alliance's strategic significance and that its character had to be redefined due to the misaligned strategic objectives of the two allies (Lee 2021, 73). It is not a recent phenomenon for the ROK and the US to cooperate in space. Even though it operated in the civilian sector, it was established in the 1990s. However, the timing of Washington's enthusiastic support in recent years, which made it possible for a number of dramatic, quick breakthroughs in South Korea's space program, appears to be related to the escalating hostility between the US and China. Despite the strong bond that Washington and Seoul have developed over the years, it seems that Washington only becomes interested in Seoul when there is a security issue in the Northeast Asian region (Wan 2010, 13).

South Korea carefully declined to participate in both the Quadrilateral Security Dialogue (QUAD) with the United States, Japan, India, and Australia and the trilateral relations with the United States and Japan that would have been proposed as part of Washington's recent efforts to isolate Beijing that involved Seoul. It is not a

coincidence that the first two world leaders from Japan and South Korea that the Biden administration invited to the White House were from these countries (Kim 2021a). Washington's decision to end the 1979 bilateral missile agreement and invite South Korea to join the NASA-led Artemis program appear to be part of a plan to confront and contain China and Russia in space while maintaining its control of space by promoting South Korea's space technology advancement to its advantage.

Notably, after negotiations with the United States fell through, South Korea worked with Russia in the early 2000s. Washington was well aware that Seoul might resume collaboration with Russia and deepen its connections with that country if Seoul was not included in Washington's space program. More significantly, the United States may have understood that ceding South Korea to China or Russia would reduce its influence in East Asia (Wan 2010, 15). As a result, from Washington's perspective, aiding South Korea with its space program was a step toward putting together multilateral coalitions to limit China and Russia and strengthen the U.S. position in the Indo-Pacific region.

### **III. The development of U.S. defense space force**

#### **1. Growing threats to U.S. space superiority**

The space environment has changed since the beginning of the 21st century. After China's intercept test in 2007 and Russia's decommissioned Cosmos 2251 satellite collided with the US's Iridium 33 satellite in 2009, the amount of space debris increased rapidly. Accordingly, the need for monitoring the space environment and establishing an international cooperative system for a sustainable space environment has increased (Choi 2015).

In addition, China conducted an anti-satellite attack test (ASAT) in 2007, and India also announced that it would develop ASAT weapons. Iran and North Korea also acquired rocket technology as they succeeded in developing projectiles. The space

environment is changing as there is no certainty of safe activities in space, such as artificial satellites and manned space flight. The U.S. Department of Defense described the space environment as complex, intimidating, and competitive (Chi 2017).

Furthermore, in February 2020, Commander of the U.S. Space Command John W. Raymond said that a second satellite was emitted from one of the first satellites launched by the Russian government in November 2019, expressing concerns about unusual and suspicious behavior near the U.S. government satellites. The pair of Russian satellites are said to be tracking US satellites within 100 miles. In addition, on April 16, Russia said that it conducted a test launch of a satellite interceptor missile, threatening the United States in space. The interceptor missile does not appear to aim at a specific target, but the US reaction was very cautious and serious. This is because the United States is the country that operates the most equipment in space.

According to the report 'Challenges on Security in Space' released by the Defense Intelligence Agency (DIA) under the U.S. Department of Defense on February 11, 2019, China and Russia are developing laser technology that can destroy U.S. satellites in space. The report dealt with the space combat capabilities of China, Russia, Iran, and North Korea and, in particular, pay greater attention to China and Russia as they are trying to counter the US space status by various means. Also, referring to attacks on satellites, it warned that there is a high possibility that they will seek to obstruct, weaken, and even destroy the operation of satellites and sensors by developing electronic combat systems, directed energy weapons such as lasers, and missiles.

In addition, Russia unveiled six superweapons in early 2018, one of which was the ICBM RS-24 Avangard, known for its supersonic speed of Mach 27. According to Putin, the development of Avangard represents a technological advance comparable to the 1957 launch of Sputnik 1, the first artificial satellite to be launched by the Soviet Union (Hecht 2019).

## 2. Before the Trump administration

The United States has announced a number of space policies since 1950s. President Eisenhower approved the Vanguard project prior to the Soviet launch of Sputnik, and established NASA in 1958. As is well known, President Kennedy declared the Apollo project, a manned moon landing project, in 1961. And President Nixon approved the Space Shuttle project, a manned space shuttle, and President Clinton launched the International Space Station project. In 2006, President George W. Bush first announced the “National Space Policy,” which contained comprehensive guidelines for government space activities, such as space security, encouraging civilian participation in space, and space diplomacy (Lee, Sohn, & Cho 2020).

President Obama announced the US national space policy with his Presidential Policy Directive-4. The Obama administration's goals for the US space policy were: a) strengthening the competitiveness of the domestic space industry, b) expanding international cooperation, c) reinforcing stable operability in space, d) guaranteeing space missions and enhancing resilience, 5) pursuit of manned and robotic initiative (Kim 2020).

In order to achieve the objectives, as guidelines for inter-agency and intersector implementation, the Presidential Policy Directive-4 suggested 1) with respect to basic activities and capabilities, ① strengthening US leadership in space, ② improving clear access to space, ③ maintenance and improvement of space-based navigation systems (location, navigation, time), retention and development of space expertise (professional manpower), ④ space system development and improvement of acquisition, and ⑤ strengthening of inter-agency partnerships.

Also, regarding “2) international cooperation”, the Presidential Policy Directive-4 presented ① strengthening the US space leadership, ② identifying potential areas of international cooperation, and ③ developing transparency and trust-building measures. In addition, 3) In relation to the preservation of the space environment and the responsible use of the space, it stated ① the preservation of the space environment and ② the development of space collision warning means. And it suggested 4) effective export control policy, 5) space nuclear power source,

6) frequency band and interference protection, and 7) guarantee of essential functions for space mission and resilience.

As a sectoral guideline, a separate guideline was announced by dividing it into commercial space field, civil space field, earth environment observation and meteorological field, land remote sensing, and space national security field. Among them, the guidelines that are particularly interesting are commercial space, space exploration, and space national security, and the core contents are as follows (Park 2020).

#### 1) Commercial space

In order to improve the commercial space industry by private companies, the government develops space industry only in cases where there is no suitable alternative to the private sector, and in unavoidable cases such as national security and public safety. Otherwise, the private space capabilities and services are purchased or utilized as much as possible. In addition, the introduction of new contracting methods (PPP, etc.), deregulation for commercial space activities, and export promotion of US companies through review of export control policies are included in the Presidential Policy Directive-4.

#### 2) Space exploration

It also clarified the missions NASA should do in relation to US space exploration, and the main contents are: 1) presenting milestones for manned space missions beyond the moon, including the mission to send people to asteroids by 2025, 2) continuous operation of the International Space Station (ISS) until 2020 or beyond, 3) supporting for the transportation of astronauts and space transport materials to and from the ISS as well as improvement of commercial space flight capabilities, 4) expanding future space activity opportunities and reduce costs and development of new technologies to enhance competence and implementation of test programs.

Additionally, it stated 5) supporting research and development of next-generation launch systems, including new rocket engine technologies, 6) continuing unmanned

space activities and robust space science programs, and 7) continuing the program of space science to analyze, investigate, and observe the sun, solar system, and space, 8) and strengthening of monitoring capabilities for near-Earth objects to protect humans from unexpected collisions between Earth and planetary objects.

### 3) Space national security

In relation to national security, the Department of Defense and the Central Intelligence Agency (CIA) are working to: 1) develop, acquire and operate space systems to support national security and support information systems, 2) ensure cost-effective maintenance of space capabilities, and 3) support critical national security interests, such as technological development and industrial capability enhancement, 4) implement and develop capabilities, procedures, and plans to ensure space missions important to national security, 5) conduct space reconnaissance for accurate and timely space situation awareness (SSA) and integrate and maintain operation of classified national information, 6) rapidly detect major space system obstacles and enhance warning capability, and 7) promote response capabilities to threatening environments and apply & develop advanced technologies.

Particularly, President Obama emphasized an international cooperative approach to solving various problems in space compared with his precedents. That is, in addition to the conventional space cooperation fields of space exploration and space science, the scope of cooperation has been expanded to include the use of space forces for space transport, space debris monitoring, missile warning, and maritime surveillance. The United States is leading international cooperation with various countries to establish guidelines for the monitoring of space debris and sustainable activities in space.

In the National Security and Space Strategy announced in January 2011, President Obama urged the United States to promote international space security cooperation and expand the mutual space agreement to share cost and risk with responsible countries. When the New Space Policy was announced in 2010, even US experts

expressed surprise at the expansion and reinforcement of international cooperative approaches. In April 2015, Deputy Assistant Secretary of Defense Douglas Robero of the US Department of Defense in charge of space policy announced that it would expand opportunities for international cooperation to the field of military space R&D, which was unimaginable until then. The background is based on the following environmental changes.

First, as the number of countries with space activities grew, the number of possible partner countries increased. Currently, 58 countries are investing more than \$10 million in the space field. In particular, in Asia, China, India, and Japan are rapidly emerging as space development powerhouses.

Second, the US is reducing its space budget as part of an effort to reduce its budget deficit. As of 2013, the average annual growth rate of U.S. public and military space budgets for five years was -3%. In 2008, the share of the US government's space budget in the global space economy was 25%, but in 2013, it decreased to 16% (Choi 2015).

### **3. During the Trump administration**

After taking office as the 45th President of the United States in January 2017, President Trump of the United States announced the first Presidential Space Policy Directive-1 in December 2017, and held the second National Space Commission meeting in February 2018. And he pronounced on the first National Space Strategy in March 2018, and the President's Space Policy Order-2 in May 2018. In addition to these official documents, Vice President Michael Pence's first National Space Commission meeting speech (October 1, 2017) disclosed in more detail the direction of the US space policy.

#### **1) Space Policy Directive-1**

Space Policy Directive-1, the official space policy document of the Trump administration, is a revision of the Obama administration's Presidential Policy

Directive-4 (June 28, 2010), saying, “The United States is sending humans to the moon for long-term space exploration and, later, perform manned missions to Mars and other destinations.” It completely revised the manned Mars exploration policy, which is the representative space policy of the Obama administration. This new policy is to further build the foundation for manned space exploration through manned moon exploration, and then conduct manned exploration of Mars. The United States has gone too far ahead of the manned exploration of Mars, and there is no country willing to respond to the United States and participate in the United States' international cooperation projects. It can be said that this is a sufficiently predictable revision of the policy, given that there has been a series of criticisms about the huge budget in Presidential Policy Directive-4 in 2010.

## 2) U.S. Space Strategy

On March 23, 2018, President Trump announced the first U.S. space strategy to promote a space policy that puts US interests first within the framework of national security policy. Firstly, It stated that space-related national security, commercialization, and private space, and international cooperation agreements are designed to put the interests of the United States first. Secondly, the U.S. space strategy embodies the American spirit and the pioneering and exploratory American tradition, and its commitment to lead the creation and maintenance of space systems essential to America's economic prosperity, security, and way of life. Thirdly, Trump's space strategy builds a national security strategy that emphasizes peace through space force, and fourthly, it pursues an integrated approach based on the following four axes.

- a) building space systems to improve the resilience, defense, and rebuilding of space
- b) enhancing war deterrence and warfighting options
- c) improving space operation through enhanced space situational awareness (SSA), information, and acquisition processes

- d) simplifying regulatory systems, policies, and procedures to further support the US space industry, and manned space exploration, enhanced burden sharing, and military cooperation to respond to threats

Additionally, it stated the establishment of the National Space Commission to provide a new direction for US space policy, the Presidential Space Policy Directive-1 stipulating manned lunar exploration, and the expansion of the human realm across the solar system with commercial and international partners.

### 3) Space Policy Directive-2

On May 24, 2018, President Trump issued his second Space Policy Directive. Space Policy Directive-2 requires specific implementation of the policies mentioned so far. First, the Minister of Transport will conduct a review of commercial space launch and re-entry before February 1, 2019. The Minister of Commerce reviews the regulation of the Ground Remote Sensing Act within 90 days, and submits a legal proposal to Office of Management and Budget (OMB) to promote the expansion of commercial remote sensing licenses within 120 days. In addition, a new plan to establish an organization with the main task of managing commercial space flight activities is submitted to OMB within 30 days. Within 120 days, reports on the activities of the United States in the frequency band policy, measures to improve the international competitiveness of the United States through the regulatory system, reports of the U.S. delegates in International Telecommunication Union (ITU) and other multilateral forums shall be submitted. In relation to export control, an amendment (draft) is submitted to the President via the Vice President within 180 days (Hecht 2019).

In October 2017, at the Udvar-Hazy Center at the National Air and Space Museum, Vice President Pence announced the significance of the National Space Commission inauguration ceremony in the presence of President Trump, relevant ministers, and members of the National Space Commission. Vice President Pence mentioned the reality of sending astronauts to the International Space Station, relying on Russia after the shutdown of the Space Shuttle business in 2011. He particularly pointed

out that the space status of the United States is being threatened by stating that especially Russia and China are developing a wide range of anti-satellite technologies that interfere with the US military power and further increasing the possibility of attacking satellite systems. He emphasized that he would firmly reclaim the leadership of the United States in space. With this policy, he announced that 1) the United States will send American astronauts back to the moon, 2) the moon will become a stepping stone and a training ground to strengthen industry and train international partners, and 3) as space is the core of American national security, the United States will develop space-related technologies to protect the national security (Alanbach 2019).

## **IV. South Korea's space development**

### **1. History and background**

The Astronomy and Space Science Institute, a subsidiary of the Korea Electronics and Telecommunications Research Institute, was founded in 1986, marking the beginning of South Korea's space development (Hwang 2021). The Korea Aerospace Research Institute (KARI), which is in charge of overseeing aerospace development, was founded in 1989. Since then, KARI has been crucial to South Korea's advancement in space. KARI, working with Britain and the United States, first concentrated on obtaining technology to create its own satellites. As a result, KITSat-1 (Korean Institute of Technology Satellite), Korea's first artificial satellite, was successfully launched from Guiana in 1992.

South Korea's efforts to develop carrier rockets in the 1990s were put on hold as a result of the 1979 missile guidelines reached between South Korea and the United States. In an effort to get technology for the construction of a booster, Seoul joined the Missile Technology Control Regime (MTCR) in 2001. Seoul inked a deal with Moscow under which the latter would give the former a liquid-fuel first stage booster that would carry Seoul's solid-fuel second stage booster and satellite after negotiations with Washington fell down owing to high costs and restrictions on

non-MTCR-related U.S. export (Moltz 2012). South Korea's partnership with Russia allowed it to launch its first research satellite STSAT-2C, weighing 100 kilograms, with its own launch vehicle and send its first Korean astronaut into space in 2008 despite the failure of their 2009 and 2010 launches (Lee 2021).

South Korea has launched more than thirty satellites since its first one was launched in 1992. (An 2020, 34). The KOMPSAT-3A (Arirang-3A), one of the country's 25 active satellites in orbit, was the first satellite developed by South Korea's private sector, which was launched from the Yasny launch site in Russia on March 26, 2015 (Kang 2015). In July 2020, the Kennedy Space Center in Florida launched South Korea's first military communications satellite into orbit using a SpaceX Falcon 9 rocket (Smith 2021).

Given the challenges it has faced in creating space technology, South Korea's list of accomplishments in the realm of space appears shorter than those of its peers, but it is still significant (Pasligh 2021). Throughout its brief 30-year history, South Korea's space development has been influenced by a variety of factors that encourage and restrain the advancement of the nation's space projects.

## **2. Encouragements for space development**

### **1) Concerns about security**

The driving force behind any nation's space program is related to its overall security concerns (Kim 2010, 515). All nations saw how American forces used space (more especially, satellites) during the Gulf War, which was later termed the First Space War, to increase force capabilities through precise guiding, positioning, and monitoring (Kim 2010, 516). communication, intelligence-gathering, surveillance, and PNT (position, navigation, and timing) capabilities (Park 2014, 13). South Korea's aim to develop a space program, however, is primarily motivated by a need to deal with a more pressing security issue: North Korea.

South Korea's intention to retain and develop its military capabilities via space is mostly motivated by North Korea's continued military might displays and ongoing

threats (Jeong 2021). South Korea needs to defend itself from missile threats from its neighbor as North Korea increases its nuclear and missile capabilities. Seoul has come to the realization that it cannot rely on American forces stationed in South Korea, which could be withdrawn at any time, to safeguard itself. The pursuit of South Korea's missile technology, which is crucial to space development, dates back to the early 1970s, when the administration of Chung Hee Park tried to develop its own ballistic missile and nuclear technologies in preparation for a potential withdrawal of American forces from South Korea (Kim 2010, 519). South Koreans are once again worried about this after former U.S. President Trump threatened to withdraw American troops from South Korea (Choe 2021).

The removal of the 1979 missile guidelines, which placed restrictions on the advancement of South Korea's missile technology, at the Biden-Moon summit in May 2021 prompted the ROK's Defense Minister, Wook Suh, to announce a plan to mass produce tactical ground-based missiles that could destroy underground artillery bases in North Korea by 2025. (Park 2021d). Seoul also disclosed its intention to purchase new submarine-launched ballistic missiles (SLBMs) to defend the nation from nuclear-powered submarines from North Korea (Jeong 2021). Minister Suh also discussed the construction of an Iron-Dome interceptor system in 2021 to counter North Korean artillery (Jeong 2021).

Seoul also aspires to be less reliant on American space technology while still being able to assess and track the threat posed by North Korea (Choe 2021). A SpaceX Falcon 9 rocket put Seoul's first military communications satellite into orbit in July 2021, and it is anticipated that it would serve as the nation's satellite-based "eyes and ears" (Choe 2021).

North Korea was not pleased with these changes. Because Pyongyang was only able to successfully test three intercontinental ballistic missiles (ICBMs) in 2017 after placing satellite spacecraft into orbit, North Korea is aware of how to employ space technology for military purposes (Choe 2021). North Korea claimed to have tested an advanced hypersonic missile as recently as September 2021 (DW News 2021); since some types of hypersonic missiles cannot be intercepted by any missile defense

system (Yoon 2021), South Korea will continue to make efforts to use space and improve its defense system. South Korea views its participation in space activities as the sole thing ensuring its existence in the space age (Hwang 2021).

The Military Space Branch has been founded as a dedicated institution to guide the advancement of military space power, according to a declaration made by the Joint Chiefs of Staff of South Korea on January 3, 2022. (Yonhap News 2022). The Military Space Branch of the Joint Chiefs of Staff is in charge of overseeing military and space-related tasks, such as developing a space strategy based on the cohesion of land, sea, and air, developing a concept for joint space operations, and developing an execution system for joint space operations in connection with each operational command (Yonhap News 2022).

## 2) Concerns about the economy

The use of space is not only crucial for a country's national security but also its economic security. Not only does space provide a lucrative opportunity for spacefaring countries (Kim 2010, 515) but also it plays an important role in ensuring a safe banking system for international economic stability (Park 2014a, 10). The use of space is essential for a nation's economic security as well as its national security. In addition to offering profitable opportunities for spacefaring nations, space also plays a crucial role in providing a secure financial system for global economic stability (Kim 2010, 515; Park 2014a, 10). Commercial ventures in the space industry are developed and expanded to explore and utilize space (Stangarone 2021). As one of the most technologically advanced nations in communication, South Korea focuses on developing and maintaining a 6G communications satellite network and its own navigation system (the Korean Positioning System: KPS), similar to the Global Positioning System of the United States, among other lucrative space developments like the global 6G network (BBC 2020), space mining (Park 2021b), space travel (Weinzierl and Sarang 2021), 3D bioprinting (Sims 2021), space-based solar power, and space waste collectors (Park 2022a) (Stangarone 2021; Clarke, Lee, and Woolnough 2021).

Hye-sook Lim, the Minister of South Korea's Science and ICT Ministry, claims that these technologies are employed to enhance the accuracy of the operation of urban air mobility, drones, and self-driving services (Bloomberg 2021; Stangarone 2021). Fast data communication anyplace on Earth is just one aspect of 6G. (the land, the sea, and air). More significantly, it will make it possible for quick data transfer between objects, which is essential for autonomous vehicles and urban air traffic (such as drones), to work accurately, effectively, and efficiently (Jeong 2021, 13). To develop and deploy the KPS, South Korea has committed 4 trillion won (more than USD 3 billion) (Kim 2021c). during the Biden-Moon meeting in May 2021, both nations reaffirmed their commitment to working together on both the U.S. GPS and South Korea's upcoming KPS (National Coordination Office for Space-Based Positioning, Navigation, and Timing 2021).

At the Biden-Yoon meeting in May 2022, this pledge was reaffirmed. The KPS will provide extremely exact positioning, navigation, and timing (PNT) information, enhancing the efficiency and functionality of gadgets utilizing urban air mobility and autonomous driving technologies in the lucrative future business (Kim 2021c).

### **3. Restraints on space development**

The 1979 Missile Note explains why South Korea's space program was delayed and didn't really take off until later. For a nation to become a space power, missile technology is essential. Without working launch technology, the nation is forced to rely on other nations to place its satellites and other space objects in orbit, losing its autonomy by being forced to share private information with others, such as payload kinds (such as classified payloads) and launch dates (Seo, Bae, and Yeung 2021).

South Korea developed and successfully tested its own missile, the White Bear (NHK-1), while Chung Hee Park was president. Although Washington promised to deliver its missile technology to Seoul, it prevented the rocket's deployment because of concern that South Korea's missile capability might incite North Korea and cause an arms race (Choe 2021; Kim 2010, 519).

Soon after, both nations agreed on the terms of the Missile Note, which capped the missile's payload at 1,000 pounds and its range at 180 kilometers while only allowing liquid fuels (Kim 2010, 519). Since then, South Korea has been prohibited from independently developing space launch rockets due to the dual usage of space launch technologies. Even though subsequent revisions in 2001, 2012, and 2017 increased ranges, eliminated payload capacity restrictions, and allowed solid fuels<sup>2)</sup> (with some exceptions), the 1979 Missile Note lasted until 2021, only after the still-classified bilateral missile agreement had significant negative effects on South Korea's space development for more than forty years.

“South Korea now has full missile sovereignty—the first such achievement in 42 years—with the elimination of the missile regulations,” South Korea's Prime Minister Sye-Kyun Chung stated on Twitter on May 21, 2021. (Lee 2021, 73). A few weeks later, the country announced plans for a number of space programs that would involve the development of missile technology through Hye-sook Lim, Minister of Science and ICT (Kim 2021b).

#### **4. Two pivotal moments in space development**

Two pivotal moments in the history of South Korea's space development are identified by Hyungjun Ahn, the head of Research Policy Team II at the Science and Technology Policy Institute (STEPI), which houses the National Space Policy Research Center. The Space Development Promotion Act, which was passed in 2005 and assisted in organizing and advancing South Korea's basic and comprehensive space development goals, marked the first turning point in the field. The second turning moment, according to Ahn, was in 2021, when a number of significant events occurred, including the cancellation of the 1979 Missile Note, the signing of the Artemis Accord, thorough proposals for the KPS, and the Nuri launch (Cho 2021).

The 1979 Missile Note was abolished at the Biden-Moon summit in May 2021. A

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2) In 2001, the missile range increased from 180 kilometers to 300 kilometers, and in 2012 it increased to 800 kilometers. The payload limit increased to 500 kilograms in 2012 and was eliminated in 2017. In 2020, solid-fueled motors were allowed (see Lee 2021).

few days later, South Korea ratified the Artemis Accords and joined the Artemis program, a NASA-led lunar exploration initiative, as its tenth member. The ROK Air Force and the U.S. Space Force announced on August 27, 2021, that they would establish a consultative body to support the two nations' collaboration on space policy and missile defense. They also agreed to conduct collaborative military exercises under American command to bolster American space defense capabilities (Lee 2021, 74).

A few weeks later, the South Korean government declared that from 2022 to 2027, it will spend 687 billion won (USD 593 million) to assist domestic aerospace companies in effectively entering the global space market through sharing state-owned space launch vehicle technologies with businesses (Park 2021c). In order to develop space policies for ROK's armed forces, facilitate cooperation with regional and international partners like the U.S. Space Force, and coordinate the activities of various entities involved in space policies, the ROK's Air Force established a space operations center in late September 2021. (Park 2021d).

Several weeks later, General John W. Raymond, the commander of the U.S. Space Force, urged further military collaboration between South Korea and the United States in space (Park 2021e). The United States and South Korea came to their first bilateral agreement on a shared space strategy in late April 2022, enhancing their capacity to deal with the escalating challenges to space security (Park 2022c).

The Space Cooperation Working Group meeting on April 25, 2021, where both parties reaffirmed their commitment to space cooperation, including “exchanging information on the space sector, developing space experts through training and exercises, and improving interoperability for joint space operations,” gave birth to this agreement (Park 2022c). A USD 619 million budget for space was planned for 2022. Despite being significantly less than that of other spacefaring nations like India, Japan, and China, it was 15% higher than what the government had originally asked, which is unusual (Park 2022b).

Ahn's assertion that 2021 was the second inflection point in South Korea's space development is supported by the sheer volume of media stories on these

advancements in the country's space program in recent months. The recent successes of South Korea's space program are unquestionably noteworthy and merit further study. But, here, we are more intrigued to learn what is causing these quick changes. The repeal of the 1979 missile guidelines and the U.S.'s active involvement in South Korea's space program stand out as the two main causes of these significant developments in the country's space development.

The repeal of the 1979 missile regulations was significant symbolically (referred to as "missile sovereignty"), but it was also significant practically since it lifted all constraints that had prevented South Korea from creating its own launch system with confidential payloads for more than 40 years (Lee 2021, 74). This enables the nation to deploy satellites at any time and any distance while maintaining the mission of space objects' confidentiality. It would also make it easier for South Korea and other space-faring nations to work together effectively because the former would no longer be dependent on the latter for the creation of launch vehicles.

South Korea's space development has advanced rapidly as a result of Washington's strong involvement with Seoul in a number of its space projects. With the 2015 Space Policy Dialogue, cooperation between Seoul and Washington on civil space concerns was established. The most recent round of new breakthroughs has sped up formal collaboration and discussions between the two nations regarding advancements in space that affect both national and international security. A more intriguing subject now is what led the United States to decide that it was time to end the 1979 missile guidelines and actively support South Korea's space programs.

## **5. South Korea's stance between the United States and China**

South Korea is caught in a difficult situation because of the relationship between the United States and China. South Korea has served as a reliable ally of the United States in the region throughout the recent years while still keeping friendly commercial ties with China. Any South Korean is familiar with the adage "America for security, China for economy," which refers to South Korea's collaboration with the United States on matters of national security and with China on matters of

economic growth. It is clear that the intention is not to propose that South Korea should cooperate with any side to advance economic or national security; rather, it is to reflect the actual situation. The phrase perfectly expresses South Korea's frustration at being sandwiched between the two superpowers.

The Cold War-shaped bipolar system had dominated all international affairs in East Asia from the 1950s until the unexpected end of the Cold War dramatically altered the bipolar structure. In the wake of it, the East Asian region saw the replacement of realistic competition under U.S. hegemony with an unprecedented neoliberal regionalism. However, by the early 2010s, as East Asia reverted to a bipolar system, such reciprocal advantages of regional collaboration led by Washington came to an end (Kupchan 2022).

Due to economic globalization, which saw China's manufacturing sector grow tremendously, China became the United States' opposing rival. China was a revisionist state that threatened American hegemony in East Asia by rejecting American principles and interests. Unfortunately, South Korea has found itself in a hazardous situation, blunting reactions that result from tension between the two superpowers while developing and maintaining mutually advantageous connections with both. The greatest diplomatic challenge facing South Korea today is choosing its place between China and the United States as hegemonic competition has spread to the field of cutting-edge technology and space exploration.

Since the end of the Korean War, the United States has been South Korea's indispensable ally in establishing its own strength. Simply put, Seoul's only partner in reestablishing and bolstering its national defense and economy was Washington (Snyder 2012; Stangarone 2013, 54). This situation was altered with the end of the Cold War. The United States was no longer South Korea's main economic partner, although the US and ROK continued their exclusive military partnership. Washington remained South Korea's friendly and helpful economic partner, sharing both the values and the benefits of the alliance. The United States' funding and favorable trade policies were crucial for South Korean political elites to keep their positions of power.

China became South Korea's main economic partner as its economic potential increased and global connectivity accelerated (Cheong 2006). As the neoliberal international order has been established in both of these East Asian nations' countries since the 1990s, their close interdependent relationship has grown stronger. Both South Korea and China made economic development their top priority, enacted neoliberal reforms, and integrated their respective economic systems internationally. This strengthened the economic ties between the two nations and brought them closer together.

The economy of South Korea is strongly dependent on trade with China. The majority of South Koreans and businesses benefit from the importation of commodities from China, while many South Korean business companies directly or indirectly earn from exporting services and products to China. Given that China is both South Korean companies' greatest market and their primary supplier of manufacturing parts, any decline in the two nations' economic ties would harm both countries' industries irreparably and cause high prices and a shortage of goods for South Korean customers. The South Korean urea crisis of 2021 demonstrates how susceptible South Korea's economy is to Chinese policy. It also demonstrates how Beijing may be a valued partner in assisting Seoul with many important economic problems.

South Korea, which relied on China for more than 97% of its urea needs, experienced an unanticipated shortage of urea solutions needed to reduce emissions from factories and diesel-powered vehicles, such as commercial trucks and public buses, as China imposed export restrictions on urea to address its own power crisis. South Korean specialists warned of a serious logistical and transportation crisis and predicted that industrial operations and diesel vehicle production will soon cease (Korean Herald 2021). However, following fruitful talks between Beijing and Seoul, the former decided to speed up the delivery of urea to the latter, avoiding a disruption to South Korea's public transportation system and supply chain (Korean Herald 2021).

In addition to being China's trading partner, South Korea joined new Chinese initiatives like the Belt and Road Initiative (BRI), Asian Infrastructure Investment Bank (AIIB), and Regional Comprehensive Economic Partnership (RCEP), which can

serve as the cornerstone of a new global economic regime,

China has an impact on South Korea that goes beyond only the economy. China's attempts to meddle in South Korea's politics have expanded along with its contribution to that country's economy. The so-called 2016 THAAD (Terminal High Altitude Area Defense) issue in South Korea shows how China leverages its economic sway over the country to further its political objectives and how susceptible the South Korean economy is to the China factor. Beijing prohibited Chinese group travel to Korea as well as K-culture (Korean entertainment, music, TV dramas, and movies) in China as a retribution for the THAAD missile installation in Seongju, South Korea, in 2016. The South Korean tourism industry suffered tremendous losses as a result of the political decision made by the Chinese leadership, especially in the Myeong-dong Special Tourist Zone in Seoul (Kim and Lee 2020). Such limitations are still in effect as of 2022, continuing to cause the South Korean tourism industry to suffer huge financial losses.

Furthermore, South Korea cannot ignore China's political influence over issues concerning to North Korea. The Korean peninsula, not just North Korea, is the focus of China's position on denuclearization: North Korea is not specifically criticized. Chinese participation in the Six-Party negotiations appears to be primarily motivated by a desire to keep the United States out of the East Asian region. But China, as North Korea's sole ally and sponsor (Lee 2020), is crucial to persuading and taming its belligerent tendencies. Therefore, it is in Seoul's best interest to preserve its mutually beneficial connections with Beijing in order to benefit from Beijing's tight ties to Pyongyang.

South Korea's economy is heavily dependent on China, and China has sway over issues pertaining to North Korea. As a result, South Korea participating in any anti-China policies would be extremely harmful to South Korea's economy and security. Thus, despite under pressure for its space cooperation with the United States, it is unlikely that South Korea would follow the United States' lead and confront China directly.

South Korea was put in an awkward situation by Washington's desire for South Korea

to work with Japan. From a geopolitical standpoint, Japan is South Korea's principal partner. Japan has been South Korea's main economic partner as it expanded its economy, despite the fact that the Empire of Japan seized the Korean peninsula in 1910 and attempted to eradicate Korean culture, language, and history. In light of this context, the United States has attempted to forge an East Asian tri-alliance with South Korea and Japan, proposing to structure the alliance from a hub-and-spoke architecture in East Asia.

However, military cooperation between South Korea and Japan is a very sensitive, contentious matter that would not sit well with South Koreans until, for instance, the concerns relating to Japanese Military Sexual Slavery (also known as “Comfort Women”) are settled. The denial and justification of the invasion of the Korean peninsula by many Japanese politicians have damaged its reputation among Koreans and prevented any serious development and implementation of future-oriented collaboration between them. The recent extreme conservative shift at Japanese politics exacerbated their rivalry, making a tri-alliance unlikely.

Washington underlined the necessity for collaboration between South Korea and Japan during the Biden-Moon summit in May 2021; Seoul's response to the proposal was lukewarm. Given the South Koreans' antagonism and suspicion of Japanese militarism, such a reaction is predicted. As long as Tokyo does not alter its stance on past problems with South Korea, Seoul will likely continue to be reluctant to embrace trilateral or bilateral military cooperation, including space cooperation (Kwon, Seo, and Bae 2022).

South Korea has to carefully choose its position between the United States and China given the growing tensions between the two superpowers in and around Northeast Asia as it moves forward with its space program to avoid offending either party (Nilsson-Wright and Jie 2021, 15). It would also need to figure out a means to keep declining to participate in the military alliance with Japan without upsetting the US. South Korea is compelled to walk a tightrope between the two major powers as competition for dominance over space exacerbates already existing tensions between them (Lee 2021, 81).

## V. Conclusion

The most recent space development in South Korea raises a question. Without a doubt, South Korea, one of the most technologically advanced nations, must have serious aspirations to explore and dominate the field of space. However, given the speed and scale of recent advancements, one must wonder what made South Korea's development in space so rapid. National security has been the main driving force behind South Korea's space program throughout its brief 30-year history of space development. South Korea has looked for a means to track North Korea's military movement and, if feasible, reduce any threat without largely relying on other countries' space technology because North Korea, which is its neighbor, frequently threatens to use nuclear missiles.

Seoul also desired to enter a promising new market before it was too late. However, the limitations imposed by the missile guidelines that South Korea and the United States agreed upon in 1979 prevented it from developing its space program. The latter believed that such obstacles were necessary because it was worried about a possible arms race between the two Koreas. The 1979 missile notes were abolished at the Biden-Moon summit in May 2021. Discussions for ROK-US space cooperation have exploded during the past few years. More than anything, China's rise appears to be responsible for these changes.

The rivalry between China and the United States has developed to include outer space, where the two try to balance one another. As a result of this tension between the two superpowers, a bipolar structure has emerged in space, with China extending its Belt and Road Initiative into space in order to assert its own authority, and the United States and its former Cold War allies on the other side. Although the U.S. side continues to dominate space for the time being, there is no assurance that this situation will stay the same (Pekkanen 2021, 2).

It appears that South Korea was persuaded to join the space alliance led by the United States and provided support to independently develop its space program. Although South Korea had long sought chances for collaboration on space programs and the lifting of all limits on space development, the circumstances that made these

objectives possible left South Korea in an awkward situation. South Korea would not want to be a part of a space alliance that is hostile to China. Even Japan, the United States' main space ally, appears hesitant to challenge China (Pekkanen 2021, 3). Japan appears to be worried about the negative effects the alliance may have given its tight economic ties to China. South Korea is in a similar predicament regarding the competition for space hegemony between the major powers.

Nevertheless, South Korea appears to have decided to join the American-led space alliance during the Biden-Moon Summit in May 2021. If one took into account the significance of the nation's long-standing partnership with the United States, it was not surprising. The commitment to space cooperation was reiterated at the Korea-US Summit in May 2022: this appears to be an alliance-based development between the two nations (Ministry of Foreign Affairs of the Republic of Korea 2022). While it may not have been difficult to forecast these symbolic actions, it would be what Seoul would do if the U.S.-led space alliance decided to directly challenge China. In addition, Seoul would choose, despite the preferences of Washington, not to work directly on any military or security project with Tokyo because of its unresolved difficulties with Tokyo.

The rivalry between the two great powers was said to have created the favorable circumstances that aided South Korea's current space development. In other words, there were restrictions on certain terms. It is unclear how long South Korea's space program will be constrained by such political factors. While waiting for a solution, South Korea should expand its network of space cooperation to include nations other than the two superpowers, like India (Lee 2021, 82).

South Korea chose to participate in international multilateral space cooperation initiatives like Global Exploration Strategy (GES), the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS), and the International Lunar Network (ILN), while continuing to be a member of the UN Economic and Social Commission for Asia and the Pacific (ESCAP) Regional Space Applications Programme for S&T in order to avoid being drawn into the regional rivalry between China and Japan (Wan 2010, 11). Former ROK President Moon was clear about the goal of the nation's

space development efforts: to build a defense system using space technology to uphold and guarantee peace (DW News 2021).

Seoul too aspires to profit from the unexplored lucrative field. South Korea's biggest challenge in the upcoming years will be how to achieve its space development goals without being influenced by political circumstances.

Considering the above, this report presents South Korea's future defense space power development strategy as follows. First, since South Korea's immediate security threats have mainly originated from North Korea's nuclear and missile development, it is essential to develop a relevant defense space force strategy to deter and reject them, such as strengthening surveillance and reconnaissance capabilities through satellites and information exchange capabilities with the United States. Based on this, our military can detect signs of North Korea's attack at an early stage, deter the North from carrying out military provocations, and repel any act of unprovoked aggression.

Second, since the development of North Korea's nuclear and missile technology has progressed faster than the development of South Korea's defense space force, it is necessary to recognize the insufficiency of South Korea's defense space force as of today and, thus, actively cooperate with the United States in the fields of, say, joint research and interoperability enhancement. However, reducing unnecessary friction with China in this regard is critical, requiring significant diplomatic efforts.

Third, the private sector's space capabilities need to be strengthened in a rapid manner, and based on this, cooperation between the public and private sectors should be promoted. Currently, the private sector is not able to make large-scale investments in the space sector due to low domestic demand. To address this, the public sector should actively create demand for satellites and launch vehicles for private entities. This will help many companies enter the global market. Through this process, as the development of the private and public sectors forms a virtuous cycle, South Korea's defense space force will be significantly enhanced.

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## **Application of Drone to Military Operations in Industry 4.0 – Theory and Algorithms.**

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## 1. Introduction

Unmanned aerial vehicles (UAVs) are also known as drones, and are becoming increasingly important in various fields in the civil and military sectors due to their improved endurance and stability in various conditions and operations. According to the Association for Unmanned Vehicle Systems International (AUVSI), there were more than 2900 UAVs across more than 900 companies providing services around the world in 2020 (AUVSI, 2020). A UAV can be described as an aircraft capable of flying and staying in the air without a pilot capable of performing critical tasks without jeopardizing human safety and operating more cost-effectively than comparable manned systems. They are remote-controlled or autopilot devices that use remote controls to perform control tasks from ground controls, allowing UAVs to perform autopilot and control tasks during flight using a variety of sensors, including IMUs and GPS. They can perform various functions such as remote sensing, transport, armed attack, and search and rescue missions. UAV may be referred to using other terminologies such as drones, unmanned aerial systems (UAS), remotely piloted aircraft (RPA), and remotely piloted aerial systems (RPAS). In this study, these systems are referred to as drones. The drones have a variety of uses in the military and defense sector (Bucaille et al. 2013 and Tesfa-Alem 2013). Drones are being used in various military operations due to their high convenience that can reduce losses and facilitate mission performance. Military drones can be classified as intelligence-providing baits that can be used for operations and battles on specific targets depending on the operation. Therefore, this research investigates applicability of the drone to military operations in Industry 4.0.

## 2. Industry 4.0

There have been three industrial revolutions since the 1800s. These Industrial Revolution are based on innovative new technologies in areas such as mechanical engineering of steam engines, innovation of assembly lines, and speed of computers etc. The reason why these events are called industrial ‘revolution’ is that they have

fundamentally changed the way goods are produced and done, not just to increase productivity and efficiency to some extent.

The Fourth Industrial Revolution, called as Industry 4.0, is revolutionary in areas such as automation, monitoring, and supply chain analysis through smart technology. Industry 4.0's underlying technologies are the Industrial Internet of Things (IIoT) and Cyber Physical Systems (CPS), a smart autonomous system that monitors and controls real objects such as machines, robots, and vehicles using computer-based algorithms. From smart manufacturing and factories to intelligent warehouse management and logistics, Industry 4.0 makes everything 'intelligent' in the business's supply chain. However Industry 4.0 goes beyond the supply chain and works with back-end systems like Enterprise Resource Management (ERP) to deliver unprecedented levels of visibility and control to the business. Industry 4.0 is ultimately an important part of every company's digital transformation.

## **2.1 The new technologies in Industry 4.0**

Industry 4.0 is based on nine key technologies. These innovative technologies connect the physical world to the digital world and realize smart autonomous systems. Many businesses and supply chains already use some of these cutting-edge technologies, but they must be combined to maximize the potential of Industry 4.0.

### **1) Big Data and AI analytics**

Industry 4.0 collects big data from a wide range of sources, from factory facilities and Internet of Things (IIoT) devices to ERP and CRM systems and weather and transportation apps. Artificial intelligence (AI) and machine learning analytics are applied to the collected data in real time and leverage insights are used into all areas of Supply chain management: Supply chain planning, Logistics management, Manufacturing, Enterprise asset management (EAM), and Procurement etc.

## 2) Horizontal and vertical integration

The backbone of Industry 4.0 is horizontal and vertical integration. In the horizontal integration, the processes are integrated at the 'field level', i.e. the processes are tightly integrated across production facilities and supply chains. In the vertical integration, every layer of the organization is connected and data is moved from the field to the management, and from the management to the field. In other words, production is closely integrated with R&D, Quality Assurance, Sales, Marketing, and other departments to eliminate data and knowledge isolation.

## 3) Cloud computing

Cloud computing is an important driving factor of industry 4.0 and digital innovation. Today's cloud technology goes beyond providing speed, scalability, storage, and cost-effectiveness, and provides the foundation of cutting-edge technologies such as AI, machine learning, and the Internet of Things, enabling business innovation. The data on which Industry 4.0 technology is based resides in the cloud, and the core of Industry 4.0 is the Cyber-Physical System (CPS), which communicates and coordinates over the cloud.

## 4) Augmented Reality

Augmented reality that overlays digital content in real-world environments is a key concept in Industry 4.0. People use smart glasses or mobile devices in AR systems to visualize real-time IoT data, such as facilities and products, as well as digitized parts, repair or assembly manuals, and educational content. Although AR is not yet commonplace, it can be applied significantly in a wide range of areas, such as maintenance, service, quality assurance, technician training, and safety.

## 5) Industrial Internet of Things (IIoT):

The Internet of Things (IoT), more specifically the Industrial Internet of Things (IIoT), is very important in Industry 4.0, and the two terms are often mixed. Industry 4.0

uses sensors and RFID tags to provide real-time data about their status, performance, or location in most physical objects, such as devices, robots, machines, facilities, and products. This technology enables businesses to better operate their supply chains, design and modify products quickly, avoid facility downtime, pinpoint consumer preferences, and track products and inventory.

#### 6) Additive manufacturing 3D printing

Additive manufacturing (3D printing) is another important technology driving Industry 4.0. 3D printing was initially used as a tool to quickly create prototypes, but it is now used in a wide range of areas from bulk customization to distributed manufacturing. For example, 3D printing can save parts and products as design files in a virtual inventory and print on demand when needed to reduce transportation distances and costs.

#### 7) Autonomous robots

The next generation of autonomous robots is part of Industry 4.0. Autonomous robots programmed to perform tasks with minimal human intervention vary in size and function and include drones for inventory scanning and mobile autonomous robots for pick and place tasks. These robots have built-in advanced software, AI, sensors, and machine vision to perform demanding and sophisticated tasks and to recognize, analyze and take action on information received around them.

#### 8) Simulation or digital twins

Digital twins are virtual simulations of real machines, products, processes, or systems based on IoT sensor data. Businesses can understand, analyze and improve the performance and maintenance of industrial systems and products using Digital Twin, a key element of Industry 4.0. For example, a system manager can leverage digital twins to find specific parts that are not working properly, predict potential problems, and increase uptime.

## 9) Cyber-security

Effective cyber-security is critical in Industry 4.0 as more parts are connected and big data usage increases. Companies can implement 'zero-trust' architectures and technologies such as machine learning and blockchain to automate threat detection, prevention, and response across the network and minimize data protection violations and production delays.

## 2.2 Advanced Technology-Driven Future Weapons Forecast in Industry 4.0

In response to the development of science and technology by Industry 4.0, future war and security environment changes in the defense sector are needed, especially predicting future technologies that meet rapidly changing technology trends such as shortening and convergence of technology life cycles. Based on the development trend of Industry 4.0 such as weapons, artificial intelligence, and unmanned, we need to present a weapon system that can dramatically improve our military's capabilities in the future battlefield environment and prepare for necessary technology development.

With the recent development of high-tech science and technology such as the use of high-tech weapons systems that can lead the future battlefield is expected to accelerate. Accordingly, it will be significantly important to investigate and analyze technology predictions in the preliminary planning stage, which integrates and analyzes future technologies and weapons systems, and to establish technology development strategies based on them.

Attempts are made to incorporate advanced technologies such as artificial intelligence, unmanned, and laser into the defense weapon system early, and based on this, preparation for future defense and security is essential by predicting information management technologies such as network-oriented command control, surveillance, and long-range strikes. Technical approaches are needed to lead the future battlefield by deriving advanced defense science technologies through analysis of future weapons systems and identifying technology gaps through analysis of domestic and foreign technology status.

### 1) Intelligent, hyper-connected, integrated network

With the growing use of the network-connected weapon systems in the future battlefields, we need to develop intelligent and integrated networks which are hyper-connected and ultra-low latency in the multi-tiered networks.

Future weapons will be systematized in a complex system that is interconnected and operated organically, and some of the systems are being changed to unmanned, intelligent and diversified. Because of the development of information technology, the unmanned network connection system has increased, and the combination of manned and unmanned combinations is generalized, and it is believed that high-speed, ultra-connected, and ultra-low delay-based networks are needed.

### 2) Korean Tactical Operations Intelligence System

In the future tactical operation environment, the rapid and accurate judgment under the vast intelligence situations is expected to determine victory or defeat, and the number of battlefield situations in which small numbers of people perform their duties in a short period of time is increased.

Data on battlefield conditions can be collected and analyzed in real time, and used as evidence for commanders to establish better operational plans. Form a team of 10 people to rescue the hostages, establish an operation plan that can be as fast as possible and prevent damage, and enter it into the system individually before the mission is deployed. Enter the operation area, share various situations with the commander in real time through collaboration with the unmanned system, and perform the mission according to the established operation plan. When you reach the point where the hostage is held, you find that the structure of the building has been damaged by the terrorist and modify the route in response.

### 3) Integrated Maritime Combat System Based on Metabus

In order to effectively carry out complex and three-dimensional maritime cooperative combat with multiple and multiple types of maritime power connected

to the network, a metaverse-based integrated maritime engagement system is established to overcome physical, temporal, and spatial limitations.

The maritime cooperative system is a key system to improve network-based maritime cooperative combat capabilities through sensor detection information sharing, wide-area threat assessment, and remote armed allocation among multiple marine platforms in cooperative maritime operations involving many and many types of maritime power.

Through the fusion of metaverse technology based on 4th industrial technology (Artificial Intelligence, AR, VR, etc.) and marine cooperative exchange system, cooperative combat control ability can be improved by utilizing the advantages of virtual environment that can overcome physical, temporal and spatial limitations.

#### 4) Ocean Monitoring System Based on Multiple Information

In order to detect anti-submarine forces with improved concealment, it is necessary to predict future marine surveillance systems such as improved performance of existing marine surveillance systems and new concept surveillance systems, and to derive technologies necessary to establish future marine surveillance systems.

The future marine battlefield environment is expected to improve the concealment of the weapon system and expand the battlefield range, limiting the detection range and reducing detection accuracy with the existing monitoring system. Accordingly, future marine monitoring needs to improve the performance of existing surveillance systems and introduce a new concept surveillance system to expand the detection range and establish a “multi-information-based marine monitoring system” that enables early detection. In addition, it is necessary to create an intrusion prediction system that can preemptively respond to enemy threats by fusing information collected from various surveillance systems.

#### 5) Missile Interception System for the Defense of Space Assets

In the future space battlefield, there is a high possibility that space war power will

be used to neutralize space assets such as satellites. Based on the development trend of these attack weapons, it is necessary to develop technologies related to the space missile interceptor system to defend them. In addition to the satellites currently in operation, many friendly assets such as the space station are expected to be placed in orbit in the future. However, since systems that attack space assets from the ground/air are already available and electrified, the pace of development of weapons systems in the future is expected to accelerate and expand.

Just as the development and deployment of various guided weapons systems highlighted the need for missile defense systems, it is predicted that space defense systems will be required to respond to satellite attack weapons systems in the future. In order to detect threats to friendly satellites and space assets early and operate a means to respond to ASAT weapons systems in case of emergency, it is likely to use a space asset defense missile intercept system in the future.

#### 6) Multi-tiered Composite Small Satellite Group

In order to quickly obtain surveillance and reconnaissance information in space, complex satellites equipped with mission equipment such as SAR, EO, and IR should be developed to support operation by obtaining day and night surveillance information in multiple layers in orbit suitable for each satellite.

The importance of a space-based system capable of operating without restrictions on borders is increasing, and the mission of a space-weapon system is evolving. Small satellites used in the future will support effective mission performance by quickly obtaining and providing surveillance reconnaissance information without border restrictions by operating various payloads in multiple layers in optimal orbit. As space weapons systems increase, ASAT systems and space debris will increase the likelihood that surveillance missions will be restricted, and active defense capabilities will be needed to respond.

#### 7) AI-based, all-territorial and unmanned complex system

In order to improve the survival of manned platform operators and expand

reconnaissance radius and armed capabilities by combining manned platforms and unmanned platforms in the land, sea, and airspace areas, it is necessary to develop a manned and unmanned complex system based on artificial intelligence (AI). The future battlefield environment will be composed of battlefield, means, environment beyond the existing battlefield components such as battlefield, soldier, weapon. In particular, the battlefield will develop from the existing concept of land, sea, and airfield integration.

Complex system (MUM-T1) is the concept of complex operation of unmanned systems that complement or replace functions of combatants to achieve cognitive, combatant viability, and asymmetric benefits of manned systems.

#### 8) Marine Biomimic Robot for Combined Mission

The marine life imitation robot will become a game changer that can innovate the future underwater battlefield environment by overcoming the technical limitations of the existing marine unmanned system. Marine unmanned systems that utilize the shape and energy sources of existing small ships or underwater movements have technical limitations in maintaining confidentiality and maneuverability due to noise, response delay, nonlinear characteristics, and reduced efficiency outside the design area.

The marine life imitation robot, which imitates the characteristics of marine life that have evolved morphological and physiological functions by optimizing the marine environment, is expected to overcome the technical limitations of the existing marine unmanned system by having excellent secrecy, toughness, mobility and efficiency.

#### 9) AI-based hyperconnected cluster drone system

The future battlefield will be expanded from the existing ground, sea, and air battlefield to a five-dimensional battlefield environment including space and cyber areas, and artificial intelligence and network technology will connect without distinction of space to create a new concept of battlefield.

The unmanned aerial vehicle system will be changed from a method of directly controlling a single drone to a concept of performing voluntary duties with the development of artificial intelligence and big data, which are technologies of the 4th industrial revolution. It is also expected to expand this and develop into an intelligent unmanned aerial vehicle system that combines multiple drones into a single flying vehicle group and connects to a network between drones to recognize the environment as a cluster and determine the situation.

#### 10) Unmanned stealth combat vehicle

As a future weapon system, core technologies such as unmanned autonomous driving, advanced attack and protection, super-connected and unmanned combat vehicles that can perform various complex operations should be secured. Future warfare will be commonplace, effect-based warfare that strikes the enemy's core forces or centers and psychologically paralyzes the enemy to achieve the purpose of war in the shortest time and minimize mass destruction. The concept of future ground warfare will also change in the direction of mobile combat systems equipped with general-purpose artificial intelligence to autonomously judge the battlefield situation and perform their duties without the control and manipulation of human combatants.

To suit this concept of future ground warfare, unmanned stealth combat vehicles are expected to serve as a key weapon system that can dominate future ground warfare with unmanned autonomous driving, active defense and advanced attack systems using artificial intelligence and multi-sensor, super-connected and unmanned combined functions, and electric energy convergence power sources.

### 3. Classification of drones

In recent decades, the development of small aerial drones, called microscopic aircraft, has increased the demand for espionage missions. Therefore, these days, efforts to design and manufacture an ultra-small air drone capable of performing

special missions are being actively carried out. These efforts have led to the development of different types of small drones with different shapes and flight modes. A recent comprehensive classification of all existing drones is shown in Fig. 1 where HTOL stands for Horizontal Take-Off and Landing.

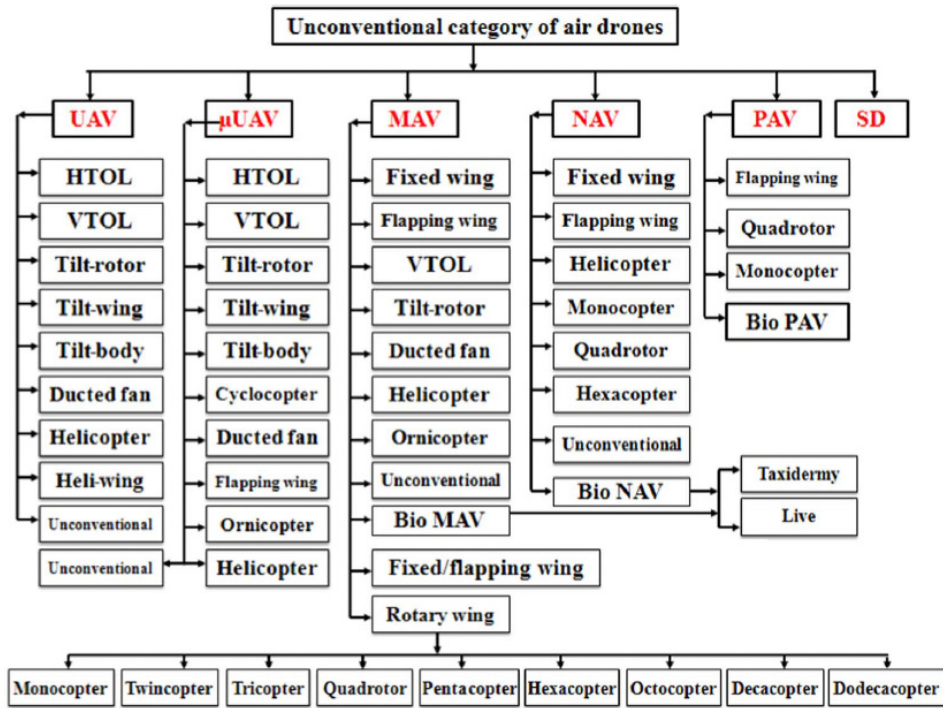


Figure 1 Different types of drones

In general, drones can be classified according to their performance characteristics. Factors which distinguish different types of drones include weight, wingspan, wing load, range, maximum altitude, speed, durability, and cost of production, and they provide an informative classification system. Moreover, drones also can be classified according to their engine types. For example, drones often use fuel engines and MAVs use electric motors. The type of propulsion system used on a drone depends on the model. Fig. 1 shows different models of drones according to their configuration. The flowchart shown in Fig. 1 also considers bio-models of micro- and nano-aircraft, defined as living controllable birds or insects and flying taxidermy birds.

#### 4. Applications of drones in military operations

The history of military drones was the Droned Fairy Queen used by Britain during World War I in the early 1930s. Since then, unmanned aerial vehicles have been built, but the military value has soared and research has been actively conducted since the 1990s. It was the Gulf War in the Middle East in 1991 that convinced unmanned aerial vehicles of their usefulness for military purposes. The Gulf War was also a test site for various high-tech weapons developed by the United States, and the performance of a few unmanned aircraft during the Gulf War was remarkable. In other words, unmanned aerial vehicles began for military purposes and are now defined as unmanned aerial vehicles, which were used to recycle old manned aerial vehicles to “air surface drones” right after World War II, and unmanned aerial vehicles were deployed to reconnaissance and information collection. Furthermore, it is equipped with offensive weapons and is used as an attacker to attack the enemy instead of ground troops.

In the 1960–75 Vietnam War, the U.S. military deployed a reconnaissance drone called Firebee to conduct day-to-day surveillance, reconnaissance, and intelligence gathering activities to identify operations and areas of interest. In addition, it contributed to successful psychological warfare by distributing a large number of psychological warfare leaflets against the enemy camp.

The 1982 Battle of Beka Valley between Israel and Syria demonstrated Israeli drone technology worldwide and promoted drone development in some countries including the United States. In the Battle of Becca Valley, Israel destroyed 15 of Syria's 17 missile bases by deploying a drone “SCOUT” to acquire targets and induce shooting. The 1991 Gulf War opened the era of military drones in earnestly.

The Gulf War ended in 100 hours after the 39-day air operation of the U.S.-led coalition, which included reconnaissance drones such as “Pioneer” to obtain information on key targets, provide reconnaissance and surveillance of Iraqi forces for 39 days. The drone's successful combat effect also affected Afghanistan and Iraq, which began in 2001, and the U.S. military reconnaissance of “Globalhawk,” a highly airborne drone capable of attacking through surveillance and firepower systems,

and “HAROP,” a battalion-level tactical unit, and a “Dragon Flack.”

In particular, in the match against Afghanistan, the Sensor to Shooter system was implemented, which immediately hit through drones, and in the match between Russia and Ukraine in 2014, Russia operated military drones such as Grusha, Eleton 3SV, Pcella, and Oran-10. In the case of high altitude drones, strategic surveillance and reconnaissance missions were carried out by focusing and operating on the border and southern coast of Ukraine, target acquisition and immediate strike were carried out through medium-range attack drones, and close combat units were reconnaissance and combat damage assessment was carried out. As such, military drones have become an important operational element in the modern war, with the United States, China, Russia, Israel, and Europe stepping up drone development and operation.

#### *Drone against Taliban*

One of the most notable uses of the drones has been in the counterterrorism role, both as an intelligence, surveillance and reconnaissance (ISR) platform and as an on-call strike platform. These armed drones are operated both by the U.S. Air Force and, in some cases (as with operations conducted over Pakistan), the CIA. Even before the 9/11 attacks, the armed Predator then in development were being considered as a means not only of keeping tabs on Osama bin Laden but also of killing him. Since then, armed UAVs have proved their worth both in the offensive strike role against specific targets and as a means of maintaining a constant level of threat.

The insurgency type of battle the Taliban adopted along with the rough terrain and unknown environment for the multinational force set the perfect grounds for drone strikes against high value targets (HVT). Starting with late 2001 US drone strikes proved effective against high value targets. Hidden locations, rough mountains, deep caves and insurgency techniques had made it almost impossible to the infantry to reach the targets. The need of a highly precise and versatile weapon appeared; that weapon proved to be the MQ-1 Predator UAV. Armed with Hellfire missiles, the Predator annihilated the HVTs that the infantry couldn't with the minimum effort and casualties, and most of the time without collateral damage.

Because in Afghanistan there were conducted US-NATO operations like Enduring Freedom and ISAF and later operation Resolute Support, most of the HVT of the Taliban movement were hiding in Pakistan. Status of Forces Agreement didn't allowed any "foot" operation in Pakistan, therefore the only resort of the coalition in order to neutralize the threat was to use air strikes against the strongholds of the Taliban leaders. The most versatile option was the UAVs like MQ-1 Predator and his larger cousin MQ-9 Reaper. The use of the drones in current warfare operations is very controversial. There are a lot of supporters, but in the same time a lot of people and organizations are blaming the use of drones especially for the inhuman treatment towards their victims and the number of civilian casualties. At the beginning of drone usage their attacks haven't been so precise and the number of civilian victims was bigger than the number of targets killed. As the time passed the strikes became more precise and effective in the same time.

### Drone strikes in Pakistan

Since 2010 the number of civilian casualties dropped from close to 20% to under 5% in 2015. The value of the targets, the impossibility of infantry troops to attack, the low number of civilian casualties and the zero loss in coalition soldiers has proved that the drones were the best choice for this type of action (Fig. 2).

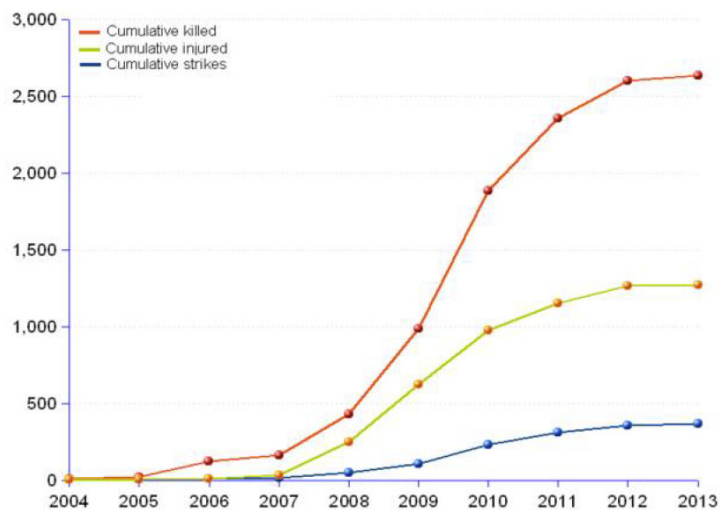


Figure 2 Evolution drone in military operations in Pakistan

As displayed in the chart the trend is ascending, but the number of strikes has dropped in order to prioritize the targets and to reduce the collateral damage. In the same time the Taliban movement has lost its popularity both in Afghanistan and Pakistan.

## 5. Optimization problems for operations of the drones

As the possible military drone applications are diverse, there are also possible related planning issues. It is important to observe that similar optimization problems may appear in other applications. Consider a drone which is required to visit multiple locations, modeled as the Traveling Salesman Problem (TSP). This problem can arise in the infrastructure industry where drones need to inspect points of interest in buildings. For example, in agriculture, drones collect information about sample points in the field; in delivery applications, drones deliver blood to multiple hospitals; in the entertainment sector, drones take pictures of tourist destinations.

### 5.1 Area coverage

In the area coverage problems, a drone or multiple drones cover various shapes of area with some objectives (e.g., minimize the cost/distance/number of turns/energy consumption while satisfying constraints).

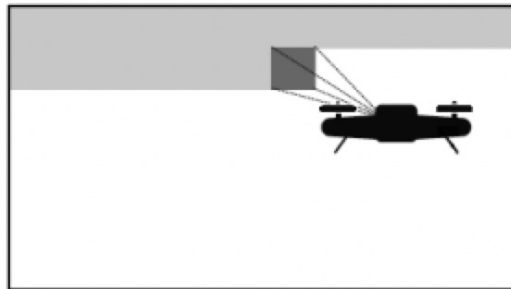


Figure 3 Area coverage

One of most important coverage problem is mimaximum information with limited coverage which can be described as follows. There are pre-determined targets that need surveillance. The surveillance required for each target is unique and can only be met with a specific sensor or set of sensors. Surveillance benefits can be obtained when drones visit targets with appropriate sensors attached. The goal of mission planning is to route the drone through the target field to maximize surveillance benefits. The problem can be formulated as a mixed integer liner programming (MILP) model.

### Indices

$i, j$	indices for targets ( $i, j = 0$ represents base location)
$h$	index for drones
$s$	index for sensors

### Parameters

$N$	number of targets
$O$	number of drones
$S$	number of sensors
$\tau_h$	maximum number of sensors that can be attached to drone $h$
$O_s$	quantity of sensor $s$ available at base
$V_{js}$	demand of sensor $s$ at target $j$
$R_{js}$	benefit obtained when sensor $s$ visits target $j$
$D_{ij}$	travel time from target $i$ to target $j$
$\lambda_h$	unloaded travel time of drone $h$
$C_s$	travel time reduction when sensor $s$ is attached
$\delta$	fuel minimization weight factor
$A_i$	earliest time target $i$ can be visited
$B_i$	latest time target $i$ can be visited
$W_{js}$	time required to deliver a single surveillance unit of sensor $s$ at target $j$

### Decision Variables

$f_{hs}$	1 if drone $h$ is equipped with sensor $s$ , 0 otherwise
$y_{ijh}$	1 if drone $h$ travels from target $i$ to target $j$
$x_{ijh}^s$	flow of sensor $s$ from $i$ to $j$ using drone $h$
$z_{jsh}$	delivery amount of sensor $s$ to target $j$ using drone $h$
$t_{jh}$	arrival time of drone $h$ at target $j$ ( $j \geq 1$ )
$t_{0h}$	return time of drone $h$ to the base

### Formulation A

$$\text{Maximize} \quad \sum_{h=1}^O \sum_{j=1}^N \sum_{s=1}^S R_{js} z_{jsh} - \sum_{i=0}^N \sum_{j \neq i}^N \sum_{ih=1}^O D_{ij} y_{ijh} \quad (\text{A1})$$

$$\text{s.t.} \quad \sum_{h=1}^O z_{jsh} \leq V_{js} \quad \forall j, s \quad (\text{A2})$$

$$\sum_{h=1}^O f_{hs} \leq Q_s \quad \forall s \quad (\text{A3})$$

$$\sum_{i=0, i \neq j}^N x_{ijh}^s - \sum_{i=0, i \neq j}^N x_{jih}^s \leq z_{jsh} \quad \forall j, h, s \quad (\text{A4})$$

$$x_{ijh}^s \leq \sum_{j=1, j \neq i}^N V_{js} f_{hs} \quad \forall i, h, s \quad (\text{A5})$$

$$x_{ijh}^s \leq \sum_{j=1, j \neq i}^N V_{js} y_{ijh} \quad \forall i, h, s \quad (\text{A6})$$

$$z_{jsh} \leq V_{js} f_{hs} \quad \forall j, s, h \quad (\text{A7})$$

$$z_{jsh} \leq V_{js} \sum_{i=0, i \neq j}^N y_{ijh} \quad \forall j, s, h \quad (\text{A8})$$

$$\sum_{s=1}^S f_{hs} \leq \tau_h \quad \forall h \quad (\text{A9})$$

$$\sum_{j=0, j \neq i}^N y_{ijh} - \sum_{j=0, j \neq i}^N y_{jih} = 0 \quad \forall i, h \quad (\text{A10})$$

$$\sum_{j=0, i \neq j}^N y_{ijh} \leq 1 \quad \forall i, h \quad (\text{A11})$$

$$t_{0h} \leq \lambda_h - \sum_{s=1}^S C_s f_{hs} \quad \forall h \quad (\text{A12})$$

$$\sum_{i=0}^N \sum_{j=0, j \neq i}^N D_{ij} y_{ijh} + \sum_{s=1}^S C_s f_{hs} \leq \lambda_h \quad \forall h \quad (\text{A13})$$

$$\sum_{j=0}^N y_{0jh} = 1 \quad \forall h \quad (\text{A14})$$

$$\sum_{j=0}^N y_{j0h} = 1 \quad \forall h \quad (\text{A15})$$

$$t_{jh} \geq D_{ij} y_{ijh} + t_{ih} - M(1 - y_{ijh}) + W_{is} z_{ish} \quad \forall i, j, h, s \quad (\text{A16})$$

$$A_i \leq t_{ih} \leq B_i \quad \forall i, h \quad (\text{A17})$$

$$f_{hs}, y_{ijh} \in \{0, 1\} \quad (\text{A18})$$

$$x_{ijh}^s \geq 0 \quad \forall i, j, h, s \quad (\text{A19})$$

$$z_{jsh} \geq 0 \quad \forall j, h, s \quad (\text{A20})$$

The first term in the objective function (A1) seeks to maximize the total surveillance benefit of all the drones, while the second term seeks to minimize fuel cost when there exist alternative optimal target sets and sensor assignments. If  $\delta$  is selected properly, the formulation will find the alternative optimal solution which minimizes fuel consumption. It is important to set a value for  $\delta$  because if the value is too large, then fuel minimization will be more important than maximizing surveillance benefit. When  $\delta$  is set according to

$$\delta \leq \frac{\min R_{js}}{O \sum_{i,j} D_{ij}},$$

fuel minimization does not take precedence over surveillance benefit. A mission planner may prefer to set a larger value for  $\delta$  if the planner expects a pop-up target to appear after the mission has started. This allows the drone to potentially have enough fuel to visit these additional targets. Constraint (A2) makes sure that the total sensor surveillance at a target can not exceed the demand of the target. Constraint (A3) ensures that the total number of sensors

attached to all drones can not exceed the number of sensors which are available at the base. Constraints (A4)–(A6) preserve sensor delivery. To ensure that a drone to provide surveillance on a target, the drone must have the appropriate sensor equipped and the drone must visit the target. These requirements are satisfied in constraints (A7) and (A8), respectively. Drone sensor capacity is represented in constraint (A9). Route continuity is ensured by the constraint (A10), and constraint (A11) does not allow a single drone to visit a target more than once. Each drone has a large flight time when the sensor payload is empty. The weight of sensor attachments reduces flight time. Constraints (A12) and (A13) ensure that the route assignments for each drone can not exceed its total adjusted flight time. This is done by limiting the time the drone returns to base to less than the adjusted flight time. Constraints (A14) and (A15) require that all drones start and end the route at the base. Constraint (A16) keeps track of the time each drone visits a target. This constraint works in conjunction with constraint (A12). It is also necessary to consider time windows in constraint (A17). Constraints (A18)–(A20) are binary and non-negativity restrictions.

## 5.2 Routing for a set of locations

In applications such as surveillance and military operations, a drone has to visit a set of locations to complete a task. In fact, drone routing issues can be useful in most applications, including construction and infrastructure, agriculture, transportation and logistics, security and disaster management, and entertainment and media. As the drone routing problems give rise to additional challenges such as the consideration of more vehicle characteristics and constraints, new modeling approaches have been proposed. For example, the battery specific issues (recharging and/or swapping), drone capacity, and payload weight on energy consumption are common considerations that are usually addressed as constraints in the optimization model.

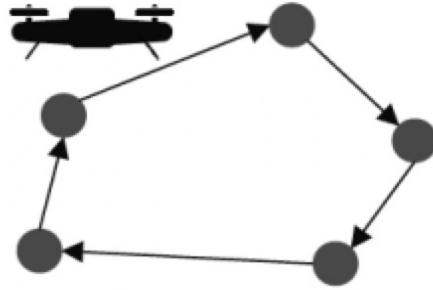


Figure 4 Routing for a set of locations

The problem can be described as follow. There exists a team of drones needed to visit a set of targets. It is assumed that the drones can carry different sensors, and therefore, there are drone-target constraints that require each drone to visit a distinct subset of targets. The problem is to find a path for each drone such that each target is visited by some drone at least once with satisfying the drone-target constraints, and the objective is to minimize the total distance travelled by the drones.

### Sets & Indices

$n$  number of drones

$D = \{d_1, \dots, d_n\}$  set of depots where  $n$  drones initially are located

$T$  the set of targets that needs to be visited by the drones

$F_k \subseteq T$  the subset of targets that must be visited by the drone initially located at depot  $d_k$ .

$C = T \cup \bigcup_{k=1}^n F_k$  the subset of all the targets that can be visited by any drone

### Parameters

$c_{ij}$  the cost of travelling from vertex  $i$  to vertex  $j$  for any drone

The problem can be formulated on the complete directed graph  $G(V, E)$ , where  $V = D \cup T$  and  $E$  represents the set of all the edges between any two distinct vertices in  $V$ . For any two distinct vertices  $i$  and  $j$ , the edge directed from vertex  $i$  to vertex  $j$  is denoted by  $(i, j)$ . For any  $S \subset V$ , let  $\delta^-(S) \subseteq E$  denote the set of all the edges directed into  $S$ , i.e., for any  $(i, j) \in \delta^-(S)$ ,  $i \in V \setminus S$  and  $j \in S$ . Similarly, let  $\delta^+(S) \subseteq E$  represent the set of all the edges directed out of  $S$ , that is, for any  $(i, j) \in \delta^+(S)$ ,  $i \in S$  and  $j \in V \setminus S$ . The problem is formulated as an integer program as follows.

### Decision Variables

$x_{ij}$                       1 if a drone is travelling from vertex  $i$  to vertex  $j$ . 0 otherwise

### Formulation B

$$\text{Minimize} \quad \sum_{(i,j) \in E} c_{ij} x_{ij} \quad (B1)$$

$$\text{s.t.} \quad \sum_{i \in V, i \neq j} x_{ij} \leq 1 \quad \forall j \in V \quad (B2)$$

$$\sum_{i \in V, j \neq i} x_{ij} \leq 1 \quad \forall i \in V \quad (B3)$$

$$\sum_{(i,j) \in \delta^-(S)} x_{ij} \geq 1 \quad S \subseteq C \quad (B4)$$

$$\sum_{\substack{(i,j) \in \delta^-(S) \\ i \in C \cup F_k \cup \{d_k\}}} x_{ij} \geq 1 \quad \forall \left\{ \begin{array}{l} S \subseteq C \cup F_k \\ |S \cap F_k| \geq 1 \\ k = 1, \dots, n \end{array} \right. \quad (B5)$$

$$x_{ij} \in \{0, 1\} \quad \forall (i, j) \in E \quad (B6)$$

The objective function (B1) is to minimize the total distance travelled by the drones. Constraints (B2) and (B3) ensure that the in-degree and out-degree of each vertex must be equal to one at most. Constraints (B4) and (B5) make sure that each common target must be connected to at least one depot and each functionally heterogeneous target is connected to its respective depot. Specifically, constraint (B4) ensures that there must exist at least one incoming edge to every subset of common targets.

Similarly, constraint (B5), requires that there must be at least one suitable edge directed into every subset consisting of common targets and at least one target from  $F_k$  for any  $k$ . For example, if the subset  $S$  consists of a target from  $F_1$  and some common targets, then a suitable incoming edge into  $S$  can be directed either from the depot  $d_1$ , or from a common target, or from a target in  $F_1$  but not in  $S$ .

### 5.3 Scheduling for Drone Operations

There are various scheduling decisions to be made in the drone operations. Such decisions may include scheduling the drones for recharging, maintenance, safety checks, etc.

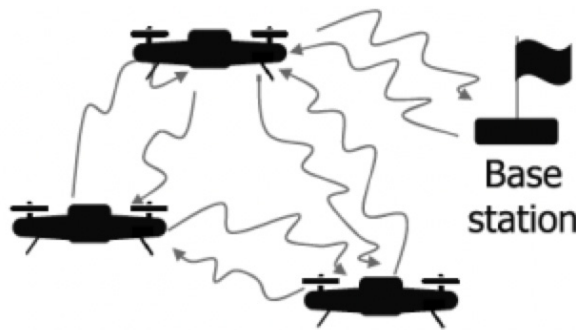


Figure 5 Operational aspects of drones

The primary goals of drone scheduling problem are to enable persistent drone operations and to assign appropriate drones for different tasks. For example, in monitoring problems, an objective is to maximize the number of objects monitored or maximize the information gathered for a fixed time constraint, which can be achieved by scheduling multiple drones. It is common to consider multiple drones for scheduling problems as scheduling is needed when there are multiple drones. The drones to be scheduled could be homogeneous as well as heterogeneous. It may require to consider energy consumption and/or payload weight as one of the important drone characteristics because it is directly related to scheduling constraints such as flight time restriction, frequency of recharge, etc.

### Sets & Indices

$r \in R = \{1, \dots, N_R\}$	index for drone flight
$k \in K = \{1, \dots, N_{drone}\}$	index for drone
$i, j \in \Omega_J = \{1, \dots, N_J\}$	index for split operation
$\Omega_{SS} = \{N_J + 1, N_J + 3, \dots, N_J + 2 \cdot N_{STA} - 1\}$	set of drone flight start recharge stations
$\Omega_{SE} = \{N_J + 2, N_J + 4, \dots, N_J + 2 \cdot N_{STA}\}$	set of drone flight end recharge stations
$\Omega_A = \Omega_J \cup \Omega_{SS} \cup \Omega_{SE}$	set of all operations and recharge stations

### Parameters

$D_{ij}$	the travel distance from the end point of split operation $i$ or station $i$ to the start point of split operation $j$ or station $j$
$P_i$	the process time of split operation $i$ or replenishing time at station $i$
$E_i$	the start time of split operation $i$
$q_k$	the maximum flight time of drone $k$
$S_{0k}$	the initial station location of drone $k$
$TS_k$	the travel speed of drone $k$
$C_k$	the purchase cost of drone $k$
$C_s$	the purchase cost of station $s$
$W_d$	the cost of drone travel per unit distance

### Decision Variables

$X_{ijk_r}$	1 if drone $k$ serves split operation $j$ or replenishes at station $j$ after processing split operation $i$ or replenishing at station $i$ during the $r^{th}$ flight; 0, otherwise
$C_{ik_r}$	operation $i$ 's start time by drone $k$ during its $r^{th}$ flight or drone $k$ 's replenishment start time at station $i$ ; otherwise its value is 0
$U_k^{drone}$	1 if drone candidate $k$ is selected to be used; 0, otherwise
$U_s^{STA}$	1 if station candidate $s$ is selected to be used; 0, otherwise.

### Formulation C

$$\text{Minimize } W_d \sum_{k \in K} \sum_{r \in R} \sum_{i \in \Omega_A} \sum_{j \in \Omega_A} D_{ij} X_{ijkr} + \sum_{k \in K} C_k U_k^{drone} + \sum_{s \in \Omega_{SS}} C_s U_s^{STA} \quad (C1)$$

$$\text{s.t. } \sum_{j \in \Omega_J \cup \Omega_{SE}} X_{S_{0k}, jk1} = 1 \quad \forall k \in K \quad (C2)$$

$$\sum_{s \in \Omega_{SS}} \sum_{j \in \Omega_J \cup \Omega_{SE}} X_{sjkr} = 1 \quad \forall k \in K, r \in R \quad (C3)$$

$$\sum_{s \in \Omega_{SS}} \sum_{i \in \Omega_J \cup \Omega_{SE}} X_{iskr} = 1 \quad \forall k \in K, r \in R \quad (C4)$$

$$\sum_{i \in \Omega_J \cup \Omega_{SE}} X_{iskr} = \sum_{i \in \Omega_J \cup \Omega_{SE}} X_{s-1, ikr+1} \quad \forall k \in K, r = 1, \dots, N_{R-1}, \quad (C5)$$

$$\forall s \in \Omega_{SE}$$

$$C_{skr} = C_{s-1, kr+1} \quad \forall k \in K, r = 1, \dots, N_{R-1}, \quad (C6)$$

$$\forall s \in \Omega_{SE}$$

$$\sum_{k \in K} \sum_{r \in R} \sum_{i \in \Omega_A} X_{ijkr} = 1 \quad \forall j \in \Omega_J \quad (C7)$$

$$\sum_{j \in \Omega_A} X_{ijkr} - \sum_{j \in \Omega_A} X_{jikr} = 0 \quad \forall i \in \Omega_J, k \in K, r \in R \quad (C8)$$

$$\sum_{i \in \Omega_J \cap \Omega_{SS}} X_{iskr} = 0 \quad \forall k \in K, r \in R, s \in \Omega_{SS} \quad (C9)$$

$$C_{ikr} + P_i + D_{ij}/TS_k - C_{jkr} \leq M(1 - X_{ijkr})$$

$$\forall i \in \Omega_J \cup \Omega_{SS}, j \in \Omega_J \cup \Omega_{SE}, k \in K, r \in R \quad (C10)$$

$$M \sum_{j \in \Omega_J \cup \Omega_{SE}} X_{ijkr} \geq C_{ikr}$$

$$\forall i \in \Omega_J \cup \Omega_{SS}, k \in K, r \in R \quad (C11)$$

$$\sum_{k \in K} \sum_{r \in R} C_{ikr} = E_i \quad \forall i \in \Omega_J \quad (C12)$$

$$\sum_{i \in \Omega_A} \sum_{j \in \Omega_A} X_{ijkr} D_{ij}/TS_k + \sum_{i \in \Omega_A} \sum_{j \in \Omega_A} P_i X_{ijkr} \leq q_k$$

$$\forall k \in K, r \in R \quad (C13)$$

$$(1 - U_k^{drone}) \leq X_{S_{0k}, S_{0k}+1, kr} \quad \forall k \in K, r \in R \quad (C14)$$

$$U_{S_{0k}}^{STA} \geq U_k^{drone} \quad \forall k \in K \quad (C15)$$

$$U_s^{STA} \geq X_{iskr} \quad \forall s \in \Omega_{SE}, i \in \Omega_J, \quad (C16)$$

$$k \in K, r \in R$$

$$C_{ikr} \geq 0 \quad \forall k \in K, r \in R, i \in \Omega_A \quad (C17)$$

$$U_k^{drone}, U_s^{STA}, X_{ijkr} \in \{0, 1\} \quad \forall k \in K, r \in R, \quad (C18)$$

$$i \in \Omega_A, j \in \Omega_A$$

The objective function (C1) seeks to minimize the total costs: drone travel costs, drone purchase costs and station purchase costs. Constraint (C2) guarantees that all drones begin its first flight from its initial station. Constraints (C3)–(C6) are service station constraints. Constraint (C3) ensures that drone  $k$  flies to split operation  $j$  in  $\Omega_J \cup \Omega_{SE}$  from a station every flight. Constraint (C4) guarantees that drone  $k$  finishes its flight at one and only one service station per flight. Constraint (C5) ensures that drone  $k$ 's end station on its  $r^{th}$  flight and start station on its  $(r+1)^{th}$  flight are identical. Constraint (C6) implies that the finish time of a drone's  $r^{th}$  flight is equal to the start time of a drone's  $(r+1)^{th}$  flight at that same station. Constraints (C7)–(C9) are split operation assignment constraints. Constraint (C7) guarantees that all split operations in  $\Omega_J$  receive service. Constraint (C8) ensures that a drone not finish its flight at a split operation. Constraint (C9) prevents each drone from finishing a flight at a start station  $s$  with index in  $\Omega_{SS}$ . Constraint (C10) gives the relationship between the start time of split operation  $i$  or station  $i$  and the start time of its successor served by drone  $k$  during its  $r^{th}$  flight. Constraints (C11)–(C12) ensure that every split operation in  $\Omega_J$  is served at its predetermined start time. Constraint (C13) ensures that the drones must return to a station before it runs out of fuel. Constraint (C14) ensures that only selected (purchased) drones serve split operations. Constraints (C15) and (C16) imply that only selected (or purchased) stations can be used. Constraints (C17) and (C18) define the ranges of the decision variables.

#### 5.4 Drone–truck combined operations

There are some advantages and disadvantages of drones (excluding large ones usually used for military purposes, e.g., fixed wing surveillance drones) when compared to traditionally used trucks when they are used for delivery purposes. Although many drones may travel faster than trucks and do not have to adhere to a particular route as long as non-permitted flying areas (airspace restrictions) can be avoided, their load capacity and travel range are limited in general. The relatively short travel range and limited capacity issues could be resolved, and the utility of drones can be further

enhanced if drones are used with ground vehicles (e.g., trucks) in tandem. Of course, a conventional passenger car or other ground vehicles may be used instead of trucks. The drone-truck combined operations (DTCO) is defined as a system in which a drone and a truck work together as a team to achieve tasks such as delivery/collection of items, reconnaissance, inspection, monitoring, etc. For DTCO consisting of one truck and multiple drones which carries out a set of tasks, it can be formulated as a mixed-integer programming (MIP) model.

### Sets & Indices

$I = \{1, \dots, n\}$	set of $n$ nodes
$I^0 = I \cup \{0\}$	nodes including depot as start node
$I^+ = I \cup \{n+1\}$	nodes including depot as end node
$I^* = I^0 \cup \{n+1\}$	nodes including depot as start and end node
$m$	number of drones

### Parameters

$t_{ij}$	truck travel time for arc $(i, j)$
$d_{ij}$	drone travel time for arc $(i, j)$
$D$	maximum drone flight range
$M^T, M_i^D$	sufficiently large numbers

### Decision Variables

$x_{ij}$	arc $(i, j)$ traveled by truck
$y_{ij}^e$	arc $(i, j)$ traveled by empty drone
$y_{ij}^f$	arc $(i, j)$ traveled by drone with load
$y_{ij}$	arc $(i, j)$ traveled by at least one drone
$\tau_i$	arrival time at node $i$

Formulation D

$$\text{Minimize } \tau_{n+1} \quad (D1)$$

$$\text{s. t. } \sum_{j \in I^0} x_{ji} = \sum_{j \in I^+} x_{ij} \quad \forall i \in I \quad (D2)$$

$$\sum_{j \in I^0} x_{ji} \leq 1 \quad \forall i \in I^+ \quad (D3)$$

$$\sum_{j \in I^0} (y_{ji}^e + y_{ji}^f) = \sum_{j \in I^+} (y_{ji}^e + y_{ji}^f) \quad \forall i \in I \quad (D4)$$

$$\sum_{j \in I^0} y_{ji}^f \leq \sum_{j \in I^+} y_{ji}^e \quad \forall i \in I \quad (D5)$$

$$\sum_{j \in I^0} y_{ji}^e \geq \sum_{j \in I^+} y_{ji}^f \quad \forall i \in I \quad (D6)$$

$$m \sum_{j \in I^0} x_{ji}^e \geq \sum_{j \in I^+} y_{ji}^f \quad \forall i \in I \quad (D7)$$

$$y_{ij}^e \leq m(1 - y_{ij}^f) \quad \forall i \in I^0, j \in I^+ \quad (D8)$$

$$x_{ij} + y_{ij}^f \leq 1 \quad \forall i \in I^0, j \in I^+ \quad (D9)$$

$$\sum_{j \in I^0} (x_{ji} + y_{ji}^f) = 1 \quad \forall i \in I \quad (D10)$$

$$\sum_{j \in I^+} x_{ji} = 1 \quad i = 0 \quad (D11)$$

$$\sum_{j \in I^+} (y_{ji}^e + y_{ji}^f) = m \quad i = 0 \quad (D12)$$

$$\sum_{j \in I^0} x_{ji} = 1 \quad i = n+1 \quad (D13)$$

$$\sum_{j \in I^0} y_{ji}^e = m \quad i = n+1 \quad (D14)$$

$$\tau_i - M^T(1 - x_{ij}) + t_{ij} \leq \tau_j \quad \forall i \in I^0, j \in I^+ \quad (D15)$$

$$\tau_i - M^T(1 - y_{ij}) + d_{ij} \leq \tau_j \quad \forall i \in I^0, j \in I^+ \quad (D16)$$

$$\tau_0 = 0 \quad (D17)$$

$$\sum_{j \in I^0} d_{ji} y_{ji}^f + \sum_{j \in I^+} d_{ij} y_{ij}^e \leq D + M_i^D \left( 1 - \sum_{j \in I^0} y_{ji}^f \right) \quad \forall i \in I \quad (D18)$$

$$y_{ij}^e + y_{ij}^f \leq m y_{ij} \quad \forall i \in I^0, j \in I^+ \quad (D19)$$

$$y_{ij}^e \leq 1 + x_{ij}(m - 1) \quad \forall i, j \in I^* \quad (D20)$$

$$x_{ii} + y_{ii}^e + y_{ii}^f = 0 \quad \forall i \in I^* \quad (D21)$$

$$\tau_i \geq 0 \quad \forall i \in I^* \quad (D22)$$

$$x_{ij} \in \{0,1\} \quad \forall i, j \in I^* \quad (\text{D23})$$

$$y_{ij}^e \in Z \quad \forall i, j \in I^* \quad (\text{D24})$$

$$y_{ij}^e \geq 0 \quad \forall i, j \in I^* \quad (\text{D25})$$

$$y_{ij}^f \in \{0,1\} \quad \forall i, j \in I^* \quad (\text{D26})$$

$$y_{ij} \in \{0,1\} \quad \forall i, j \in I^* \quad (\text{D27})$$

The objective function (D1) is the last arrival time (of either the truck or a drone) at the depot which is to be minimized. Constraints (D2) maintain the flow of the truck at each node, while constraints (D3) ensure that the truck arrives at each node at maximum once. The set of constraints (D4) ensures the correct flow of drones and (D5) forces the drone to do an empty leg after completing a task. Constraints (D6) and (D7) ensure that a full drone flight is only starting from nodes where both, an empty drone and the truck arrived so that the drone can carry out a task from the truck. Set of constraints (D8) makes sure that a leg used by the full drone cannot be used by an empty drone. (D9) ensures that truck and full drone do not travel together on any leg. The fulfillment of the task of each node is secured by (D10). Sets of constraints (D11) to (D14) ensure that the correct number of trucks and drones start and end at the depot. (D15) and (D16) set the arrival time (the time both, truck and drone have arrived and can then depart again) of all nodes. This time is set to 0 for the departure from the depot by (D17). Note that in this model, the truck and all drones always leave at the same point in time from a node. Hence, it is not possible that a drone is launched while the truck is still waiting for a different drone. (D18) ensures that the maximum drone range is respected. For each node that is visited by the drone, the total length of the in- and outbound flight have to be below the maximum range. If a node is not visited by the drone, this constraint is non-binding. Thus, empty drone flights that are actually joint drone-truck legs are not considered for the maximum range constraint. (D19) sets the value of the auxiliary variable and (D20) limits the number of empty drones on a leg to  $m$ , if the leg is also traveled by the truck, and to one otherwise. Since we define the variables also for legs starting and ending at the same node, we have to forbid this kind of travel with (D21). We are aware that we could also just not define these

variables. However, we believe in this way the formulation of the model is more straightforward and any state-of-the-art solver will eliminate these variables easily while pre-solving. Note that this does not forbid the drone or the truck to stay at the depot, as the depot node is duplicated. Finally, the domains of all variables are defined by (D22) to (D26).

### 5.5 Data gathering in a wireless sensor network (WSN)

Drones can be also useful at data gathering in a wireless sensor network (WSN) where stationary wireless sensors need to transmit environmental data to the base station through drones.

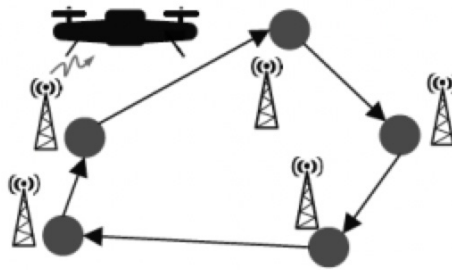


Figure 6 Data gathering in a WSN

In the wireless sensor network, there exists a set of identical drones which collect the information and pass to a single base station. Each drone can preprocess its data, using application-specific knowledge, to decrease its size. If a drone compresses its data, then it can start sending the compressed data only after the compression process is finished. Although all drones are identical, their locations are different, and this implies that the communication capabilities might not be identical for all the drones. Only one drone can be allowed to communicate with the base station at a time. Constructing a feasible schedule for the problem consists in selecting which drones should compress their data and what should be the order of communications with the base station. The objective is to develop a feasible schedule for transmitting all collected data with minimizing the total completion

times. This problem can be formulated as follows.

### Sets & Indices

$j$  indices for drone  
 $N = \{1, \dots, n\}$  set of  $n$  drones

### Parameters

$a_j$  data transmission time of drone  $j$  without data compression  
 $b_j$  amount of time reduced by data compression of drone  $j$   
 $D$  time required for data compression

### Decision Variables

$S_i$  start time of data transmission of drone in the  $i$ th position in the transmission sequence  
 $x_{ij}$  1 if drone  $j$  is in the  $i$ th position in the transmission sequence and starts its transmission before  $D$ . 0 otherwise.  
 $y_{ij}$  1 if drone  $j$  is in the  $i$ th position in the transmission sequence and starts its transmission after  $D$ . 0 otherwise.

### Formulation E

$$\text{Minimize} \quad \sum_{i=1}^n \left( S_i + \sum_{j=1}^n (a_j x_{ij} + (a_j - b_j) y_{ij}) \right) \quad (\text{E1})$$

$$\text{s.t.} \quad S_{i+1} \geq S_i + \sum_{j=1}^n (a_j x_{ij} + (a_j - b_j) y_{ij}) \quad \forall j \in N \setminus \{n\} \quad (\text{E2})$$

$$\sum_{j=1}^n x_{ij} \leq \frac{D - S_i}{M} \quad \forall i \in N \quad (\text{E3})$$

$$\sum_{j=1}^n y_{ij} \leq \frac{S_i - D}{M} \quad \forall i \in N \quad (\text{E4})$$

$$x_{ij} + y_{ij} \leq 1 \quad \forall i, j \in N \quad (\text{E5})$$

$$\sum_{i=1}^n (x_{ij} + y_{ij}) = 1 \quad \forall j \in N \quad (\text{E6})$$

$$\sum_{j=1}^n (x_{ij} + y_{ij}) = 1 \quad \forall i \in N \quad (\text{E7})$$

$$x_{ij}, y_{ij} \in \{0, 1\} \quad \forall i, j \in N \quad (\text{E8})$$

$$S_i \geq 0 \quad \forall i \in N \quad (\text{E9})$$

The objective function (E1) seeks to minimize the total completion time. Constraint (E2) implies that the starting time of data transmission of drone in the  $(i + 1)$ st position in the transmission sequence is greater than or equal to the completion time of the drone in the  $i$ th position. Constraints (E3) and (E4) imply that the transmission time of the drone in the  $i$ th position in the transmission sequence is  $a_{[i]}$  if the drone starts before  $D$  and that the transmission time of the drone in the  $i$ th position in the transmission sequence is  $a_{[i]} - b_{[i]}$  if the drone starts after  $D$ . Note that  $M$  is a sufficiently large number. Constraint (E5) implies that a drone starts either before or after  $D$ . Constraints (E6) and (E7) imply that exactly one drone occupies exactly one position in the transmission sequence. Constraint (E8) implies that  $x_{ij}$  and  $y_{ij}$  are binary variables. Constraint (E9) implies that starting times of the data transmission of drones are non-negative. Observe that Constraint (E10) is stronger than Constraint (E3).

$$\sum_{j=1}^n x_{ij} \geq \frac{D - S_i}{D + 1 - \min\left(D, \sum_{j=1}^{i-1} a_j\right)} \quad \forall i \in N \quad (\text{E10})$$

Therefore, Constraint (E10) can be used instead of Constraint (E3) to reduce a search space in finding an optimal solution.

## 6. Barriers to implementation of the drone operation.

Despite the recent surge of interests on the drone operation, a number of existing or potential barriers still need to be addressed before practical implications can be made.

## 6.1 Privacy issues

Drones may be seen as a serious threat to privacy by the general public. Drones are rapidly evolving into a smaller but more functional device with various sensing and communicating technologies. In particular, a surveillance drone, either individually or as part of fleet, is expected to be present almost anywhere for traffic management, pro- or post-event management, surveillance against crime (e.g., police and border patrol), nature conservation, etc. It is natural that the general public may feel the presence of drones very uncomfortable or may consider them as an infringement of privacy if surveillance drones are hovering around them.

Mass data collection via drones can be worrisome. For example, in search-and-rescue operations and surveillance operations, drones may have to take random pictures without permission, which may be taken as 'search without warrant'. Small drones may make the concern worse because it is very difficult to see them in the sky, and people may not notice even when they are observed by the drones.

## 6.2 Security issues

Communication is a critical part for a drone or a fleet of drones both in manual (e.g., control signal) and autonomous (e.g., GPS signal) control and operations. Many drones are also expected to transmit collected time-sensitive data through communication links rather than saving it until they return to the base. Despite the continuous effort to protect the communication protocol such as security framework or cryptographic schemes, drones are always exposed to various types of cyber attacks and can become vulnerable as long as they are communicating through the air.

The compromised communication issues are naturally connected to the concerns

about using the drones for cyber-physical attacks to both private and public sectors. An attack to the drone itself may also be possible by, e.g., fake GPS signals or interference in control. Some ways to prevent drone attacks can be done by identification of unauthorized drones, drone hackers, and routes of such drones.

Another concern is the usage of collected and leaked data. If the private data is sold without permission to a commercial entity, shared in the social networks, and gathered by national security agencies, it could lead to another serious issue that is related to civil liberties. If the collected data is about sensitive facilities, the security issue can be more critical because it can be used for both cyber and physical attacks.

### **6.3 Safety issues**

In general, safety issues of drones are coupled with the security issues because insecure control of drone, whether from malfunction or hacking, may cause accidents by falling into the ground or by a collision in the air. A proliferation of drones may make this issue more complicated because not only the chances but also the causes of accidents may increase in proportion to the number and types of drones. The use of different altitudes for different types of air vehicles would not be a complete solution because a collision may happen during landing or takeoff. Therefore, there is a continuous need of considering extensive scenarios for regulations and corresponding training programs to address the anticipated safety issues.

### **6.4 Environmental issues**

Drones may have a negative impact on physiological health of wildlife by increasing stress level due to the noise (unique buzzing sounds) when the drones fail to keep the distance. If wild animals are exposed to such environment for a long time, it could lead to wildlife disruption because such impact may be particularly serious with animals that are pregnant or raising the young. There is also possibility of

drones to hit birds and other wildlife animals. As drones are expected to become more widely used, they would fill the sky similar to how vehicles are on the roads. This may cause both visual (e.g., shadows) and sound (e.g., buzzing noise) pollution to the general public, as the drones would be seen everywhere leading to a phenomenon called full skies. Drone operation is also not free from CO2 emission issues. Electricity to recharge batteries may be generated from burning fossil fuels. In addition, fossil fuel-powered trucks may also be used in the drone operation. In contrast to the general belief that drones are much more environmentally friendly than conventional trucks, drones may cause more emissions especially when the operation distance is very long.

## **6.5 Socio-economic issues**

New technologies such as autonomous drones and autonomous trucks may replace a number of human jobs and may cause economic issues such as mass unemployment or polarized economy. There will be opportunities for new skilled jobs for the drone operations while the number of old replaceable jobs may decrease. Therefore, adopting the new technology needs to be agreed upon between diverse economic stakeholders by appropriately considering and interpreting the anticipated potential impacts.

## **7. Military applications of the drones in the case of South Korea.**

As for the topographical characteristics of Korea, 70% of the land is mountainous. In particular, 80% of the North Korean region is made up of mountains, and there are about 80 mountains of 2,000m or more. It has severe ups and downs due to the skewed mountain ranges in the east and gentle slopes in the west, and most parts of South Korea are lush with vegetation, but North Korea has few vegetation and consists of highlands. In addition, the road network developed from east to west and north to south, and the North Korean area is restricted from maneuvering

due to its weak road network and severe ups and downs in the topography.

Contrary to the eastern mountainous terrain, the western maritime area has significant advantages in observing and building forward bases as an island area, but like mountainous areas, it has limited factors in supply of materials and access to ground troops. In addition, due to the development of large and small rivers and rivers, there are many restrictions on ground and aerial maneuvering, but water penetration is somewhat easy due to the development of rivers from the sea to the inland.

Similarly, in drone operation, an automatic navigation system should be established to automatically visit programmed areas or return to mortgages in case of remote signal loss to prevent equipment damage caused by transmission and reception disconnection caused by high and low terrain.

An important factor in the drone operation environment of the Korean military is the size of the operational area in the future battlefield environment. When the Ground Operations Command is established, the operational responsibility area of the subordinate corps will be expanded three to four times as it will be adjusted to n regional and n mobile corps under the command of the Joint Chiefs of Staff. The military's operational responsibility area will be expanded from 30 kilometers in front and 70 kilometers in depth to 60 kilometers in front and 120 kilometers in depth. The operational radius of searcher, the corps-level reconnaissance drones currently in operation in the Army, is 80 kilometers and 100 kilometers, respectively, and it will be somewhat difficult to use as transport drones to carry heavy weights from the corps command center to the enemy rear area. This will require a remote control system or GPS automatic navigation equipment that can be received from a long distance to maximize operating time through improved battery performance or aerodynamic design.

## 8. Conclusion

This research investigates applicability of the drone to military operations in Industry 4.0 focusing on optimization methods for the drone operations. Drones will bring us a better life with devices that humans can't do or can replace dangerous and hard work. However, the reality cannot be ruled out that it can pose a great threat to people if it is used for reconnaissance and attack at any time. We have seen scenes of fighting using drones or robots through movies and dramas. These scenes in the movie are now real to us, accelerating the development of science and technology and changing the real environment in the era of the Fourth Industrial Revolution.

In particular, drones can serve as a test bed that can apply the common core technologies of the 4th industrial revolution along with technologies such as the Internet of Things (IoT), artificial intelligence (AI), sensors, and 3D printing, so there is a lot of interest, including the United States. Countries are making great efforts to achieve dominance in the drone industry, and developing core technologies to use drones for military purposes. In addition, a lot of research and investment in manned-unmanned integrated combat and unmanned combat systems, including drones, are spared, and even combat experiments are being conducted.

Here in South Korea also unmanned combat systems, such as robots for Defense Development and the private sector and research institutes, research is needed about the study related to, but it is poor situation. Therefore, in terms of military unmanned systems and oil - an unmanned combination of systems such as employment concept for reality and for a future for policy, to see that this revamped and the establishment of the ongoing implementation should be made. In addition, the number of drones, such as hobbies, leisure, industrial, and military purposes, is rapidly increasing, so related stakeholders should work together to establish a drone identification and control system.

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