Overview of the Nordic Challenges for Unmanned Aircraft Systems

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Abstract— **The Nordic countries have an intermediate climate with actual four seasons. The weather here varies from summer hot to winter, freezing with rain and snow and all the water elements between them. In this paper, we will investigate the Nordic challenges for Unmanned Aircraft System operations. We have classified them into technological and operational categories. In a recent white paper, MIT Lincoln Laboratory concluded that drone pilots needed to account for ten weather parameters to ensure a successful flight of their UAS. We see, based on our long-term experience and extensive literature review, that these parameters need to be understood what is their meaning on the technological and operational level. We push these learnings on our DroneMaster project to bring education for professional UAS operators.**

I. Introduction

Future autonomous mobile systems will be capable of operating in often unstructured and dynamic environments in a safe and meaningful manner and simultaneously work towards given mission objectives without being extensively controlled by human operators [1]. In this work, the focus is on Unmanned Aircraft System (UAS), their recent advances and further challenges. Special attention is given to the requirements the Nordic location places on the application of UAS. The Nordic weather conditions are often harsh and include a wide range of phenomena. At the same time, technology, readiness level of using UAS advances, which results in regulative actions. New EU regulations are taking place at the beginning of 2021, such as EU 2019/945 [2] and EU 2019/947 [3].

These days the application of UAS in cold and harsh environments such as the Arctic and Antarctic are extremely broad. They include remote sensing in fluvial environments [4], wildlife [5] and airborne [6] monitoring and population ecology [7], tracking of river ice [8] and sea ice movement [9], snow extent mapping [10], estimating the mass and body condition of animals [11], air quality measurements [12], spatial ecological and landscape surveys [13], observing the atmospheric phenomena [14], boundary layer [15] and profiling [16], monitoring changes on a construction zone [17], military purposes [18] among others. The Nordic weather conditions, especially in the winter season, and the UAS technology maturity are challenging for the end-users in these application areas. At the moment, there are some technological solutions available that give the components of the Unmanned Aircraft (UA) cover from such weather conditions as rain, but the winter conditions will affect the UA's even more substantial. Besides, the weather can also affect the payloads operational properties, like cameras and sensor platforms, for example. Most of the time, these payloads do not have any specific Ingress Protection (IP) [19] and therefore wind, rain and freezing temperatures might cause malfunctions in them.

With the rapid growth of Arctic tourism, UAS consumer applications are becoming more prominent in addition to the UAS being used professionally for research, business and military purposes [20]. Furthermore, the non-commercial use of UAS applications is increasing for the benefit of society. UAS can be used, for example, in humanitarian aid, environmental protection, emergency response, responsible journalism and even activism by private individuals, academic researchers, journalists, non-governmental organisations (NGOs) and even public services and commercial structures [21].

The UAS have become popular even among regular consumers in addition to enthusiasts and professionals. Most of the developed countries have introduced national and international regulations regarding the use of UAS during the 2010s [22], [23]. However, the applicability, technical requirements, operational limitations, administrative procedures, and ethical constraints vary significantly between the countries [22]. In most cases, regulations have not been able to keep up with the rapid emergence and development of UAS technology. Thus, placing barriers on research, development, market opportunities and social gains [22].

The DroneMaster project (2020-2023) [24] is developing online education for professional UAS operators. Due to the geographical location of Finland, many professional UAS applications and UA missions take place in very challenging weather conditions. For that reason, the project team has collected the technical and operational requirements for the UA missions systematically.

The DroneMaster project [24] conducted qualitative research using two questionnaires which have indicated how the UAS operators and remote pilots utilise UAS in the Northern Ostrobothnia area of Finland. From the first questionnaire results, it was possible to point out that 77 per cent of the UAS operators use commercial UAS solutions, which are typically not intended to be used in harsh weather conditions. The second questionnaire focused on how the remote operators used UAS solutions in the Nordic conditions and what was the impact on the environment. It was found that 96 per cent of the UAS operators check the weather forecast before the flight operation. The lowest reported temperature during the UAS mission was --33 °C. Seventy-five per cent of UAS operators reported that the freezing phenomenon had a negative effect on the UA during the operations. Over 91 per cent of UAS operators are pre-heating and storing their flight batteries in a warm place before flight operations. Overall, the professional pilots are well aware of how the Nordic conditions affect their equipment's and how they need to plan their operations. The results of the questionnaire reveal that end users are interested in getting better guidance from equipment manufacturers on how the equipment should be used in cold weather conditions, as well as new solutions, both software and hardware, that could allow better use of UAS in cold weather. It was also found that the end-users would like to have more information regarding the new European Commissions legislations (EU 2019/945 [2] and EU 2019/947 [3]) as well as modern UAS technology maintenance aspects and what are the best practices to operate UAS.

Within the scope of this paper, the following acronyms and terms are to be considered interchangeable as they all are used in reference materials: Unmanned Aerial Vehicle (UAV), UA, and drone.

II. The Nordic Challenges

The Nordic countries have an intermediate climate with four seasons. In most Nordic countries, the summers are bright and warm, and winters are dark and cold. It is common to have heat waves during the summer season when temperatures will rise to almost 40°C. During the winter season, the temperatures can plummet up to -40 °C, and the lowest recorded in the Arctic is -68 °C. Depending on the definition, the Arctic region starts north of 60° north latitude or north of the Arctic Circle (66°33'44" N). Already during the autumn season, there can be quite a lot of high rainfall, snowfall and darkness since the daytime get ever shorter as the upcoming winter Polar Night draws closer. During that time, to the north of the Arctic Circle, the sun does not rise at all. After the Polar Night has passed, the daytime grows longer until it is the longest during the midsummer when the summer solstice occurs. During that time, to the north of the Arctic Circle, the sun does not set at all.

The Nordic challenges for UAS operations are categorised into two categories: technological challenges and operational challenges [25][26].

A. Technological challenges

Technological challenges are those that may be addressed, and their impact reduced or eliminated with the development of technologies, improved design or functionality of UAS, more sophisticated construction materials or application of additional technological means or artefacts. Some of the technical challenges may also be considered as operational challenges since they are relevant to the weather conditions and may be affected by human actions (e.g., cancelling or rescheduling UAS missions) [25], [26]. The overview of the technical challenges presented in alphabetical order is following.

AI data post-processing is widely used whenever volumes of data, requirements for processing speed, other demands or processing-specific requirements do not match with the ability of processing by humans. One of the typical AI application areas for data post-processing is 3D mapping [27] and other photogrammetry tasks [28]. Although with the current development of UA computing capacity, it is possible to build 3D models of the environment as a part of operational AI, e.g., for navigation purposes [29]. A considerable number of applications relevant to monitoring, mapping and observation UAS require data post-processing, e.g., in forestry [30].

AI operational could help UA with processing vast volumes of operational data to achieve higher operational efficiency. For example, autonomous and assisted flight control systems may use machine vision, data fusion, machine perception, and AI-enhanced communications and data security to perform flights within set ethical principles and interact with UA's remote pilot through adaptive multimodal interfaces. With the help of operational AI in the future, it will be possible to carry out fully autonomous missions [31], also, life-critical [32]. Ethical considerations concerning AI are relevant to operational challenges [33].

Assistive and mission-specific sensors is a huge area of technological development that progresses along with non-specific to UAS sensor development. A vast number of sophisticated assistive and mission-specific sensors for UAS are developed worldwide, and yet more to come. The UA sensor technologies [34] may include a range of cameras [35], [36], deployment, integration with IoT services [37], utilise data fusion [38] and be implemented as a multi-UA setup [39], which may also be organised as UA swarms [40]. Sensor accuracy may be crucial in some application areas [12].

Battery technologies are important regardless of UAS power sources. Even aviation gasoline-powered UA may have battery-powered ignition and computing boards. Battery technologies have developed over the years but are still prone to charge loss and voltage drop and loss under low temperatures. Battery capacity, keeping the suitable temperature conditions, alternative energy sources, and energy harvesting are matters of cutting-edge R&D&I activities these days. These challenges [41] are addressed from both ends, by developing more sophisticated battery technology [42],[43], [44] and by optimising the energy expenditure [45], [46]. The battery technology challenges are relevant to weather physics challenges [47].

Body materials, main construction and moving parts may serve a multi-purpose, generic UAS or be designed for a specific application or even an extremely specific mission. Different classifications of UAS exist [48],[49]. In Europe, one of the proposed classifications for small UAs under 25 kg is by Maximum Take-off Mass (MTOM) [2], while light UAs up to 150 kg and large UAs more than 150 kg are not classified further. Depending on the construction type, different design challenges appear [48]. Some of the earlier research suggests that fixed-wing lightweight UA would be suitable for a wide range of operational environments, including maritime, mountains and arctic environments [47],[50]. Extra strong elements of UAS are produced using composites, which are very strong, stiff, and durable, and at the same time lightweight (e.g., Carbon Fibre-reinforced composites (CRFCs)). Newly developed materials have high chemical resistance and keep their properties in a wide range of temperatures. Carbon nanotubes (CNTs) may be used to build electric-powered coating that prevents icing of UA. Composite additive-enhanced materials may be 3D printed [51].

Beyond Visual Line of Sight (BVLoS) missions bring a broad range of technological challenges associated with communications, remote controlling, re-routing and other operations of autonomous or assisted navigation, localisation, operational AI, data protection and cybersecurity [52],[53],[54],[55]. In the case of multiple UAs missions [56], like swarms of UAs, the challenge is even more severe [57].

Changing the density of the air or change of *atmospheric pressure* is a challenge to the performance of the UA [58]. The lower density of the air, which typically appears at higher altitudes, negatively impacts lift and thrust forces [59]. Especially challenging for UA may be crossing the front of two areas of different densities of the air or falling into the air pocket. The flight-assisting automation may be programmed to reduce the negative influence of crossing the front and falling into the air pocket, while enhanced efficiency of UA engines and aerodynamic properties improve the behaviour of UA at higher altitudes [59].

Communications expose a broad range of challenges [49], [57], [60], [61] associated with inferior quality of communication channels, absence or out-of-reach of required communication infrastructure, and insufficiency of communication parameters. Internet access may be absent, and even the satellite Internet connection may not always be operational in the Arctic, also a subject of weather or location conditions (e.g., no connection in narrow rocky gaps). In general, any form of wireless communication is affected by those conditions and may be distorted or lost. That may affect communication of different purposes, such as vehicle-to-vehicle (V2V), swarm, air-to-ground (A2G) and command and control (C2) with ground control station (GCS). In the case of radio communication, it may be affected by magnetic storms or electromagnetic interference. Some radio frequency bands may be a subject of licensing or reserved. Certain methods aimed at improving communications as a part of disaster management [62] may be utilised for other UAS applications in areas with poor communication infrastructure.

Computing capacity is always a compromise in autonomous systems [63] with limited capacity power sources, a wide range of sensors, intensive communications, and demand for energy-hungry data processing [48], e.g., big data processing [64]. Modern microprocessors are powerful and energy-efficient so that not only control but also some data processing and analytics functionality may be performed onboard. Multilateral computation by principles of edge computing and supported with cloud services boost computation abilities. Still, in case of no or poor connectivity, the unilateral computation may be beneficial. Edge computing may bring certain benefits to UAS computational architectures [65].

Control interfaces may help eliminate human limitations and assist in decision-making processes [66]. Human-robot interactions have been researched well before the UAS era [67]. Similar principles apply and may be enhanced with assistive technologies [68]. Innovations relevant to UAS control interfaces range from direct controlling (e.g., using gestures, 3D interfaces or first-person view (FPV) video streaming-enhanced systems) to comfort mobile operator's control centres. More specific control interface requirements may come from the UAS application domain, e.g., infrastructure inspection [69], civil engineering [70].

Dust and solid particles clouds that blow from the ground as a result of take-off and landing or can be brought with masses of air may temporally alter or disable visual contact and communication with UA and the performance of its optics-equipped sensors. The small particles entering to mechanical parts of UA may bring extra friction and alter mechanical performance. UA flight in a cloud of tiny solid particles results in poorer flying performance and shorter battery life, as well as possible loss of visual contact [58] and communication. UAS are used to research the distribution of ultrafine particles in the air and air quality [12],[71], while dust and solid particles in the air may also damage UA sensors. Therefore, additional protection may be needed [72]. Solid particle and liquid ingress protection determine two important yet basic properties of environment tolerance of UA. The levels of protection are known as IP Codes or International Protection Marking, which are classified by IEC 60529 standard [19]. It is important, though, that not only UA but also onboard and gimbal-attached equipment would have appropriate protection. The higher level of protection means a better tolerance, but it concerns the specified property only and does not cover a combination of external factors affecting the performance of UA. For example, heavy rain or dust storms may not break the seal of UA but jeopardise its operation by bringing conditions that exceed the capacity of the UA aerodynamic.

Electromagnetic interference causes problems in communications and may cause hazards in UA electronics. Electromagnetic shielding is used to protect the electronics [73], but antennas are always exposable. Counter-UAS (C-UAS) technologies use the highly focused high-power electromagnetic pulse to cause hazards in electronics [74].

Extreme light conditions are always challenging for optical sensors. The conditions are typical in the Arctic. During the cloudy days, harsh weather, twilight and night-time, there may be low light or no light conditions. During the bright sunny days, especially in the winter, when the sunlight is reflected from horizon-to-horizon snow and ice masses, there is an excess of light. These conditions bring special requirements for any optical equipment used with UAs, particularly – their exposure and white balance properties and abilities. The machine vision technologies may be enhanced though [34],[75],[76].

Freezing rain and ice fog are some of the weather physics challenges [77] that are brought by instantaneously crystallising water particles. It may cause icing of contacts – that changes electrical properties or breaks the conductivity; forms icy masses on propellers and wings [58] – that worsen aerodynamic properties; or a body of UA – that negatively affects the aerodynamic properties; or forms icy masses on a body of UA – that affects negatively to the overall balance of UA in the air and may even lead to a jam of the flight control elements. Partially, these challenges may be addressed with technology advances related to ice protection and de-icing and dynamic ice accretion [78],[79],[80],[81],[82].

Heavy and gusty wind is one of the weather dynamics challenges [41],[77] that negatively affects the control of UA and its battery life. The wind having a speed about the speed of UA or higher may compromise a mission and make impossible a return of UA by blowing it away. At higher altitudes, the wind speed may be significantly higher than at lower altitudes, while closer to the surface, wind changes the aerial performance of a UA [58]. It is challenging to develop an automated piloting algorithm to compensate fast varying speed of the wind. This challenge may be addressed by, e.g., with advanced control [83] or aerodynamic models and improved control performance [84].

Heavy clouds are among the weather physics challenges [77],[58] that negatively affect satellite signal reception required for positioning systems, such as Global Positioning System (GPS). Also, the clouds may make it difficult or impossible to have visual contact with UA [58]. Partially, these challenges may be addressed with advances in navigation and communications technologies [49].

Infrastructure requirements are sometimes critical for UA missions. For example, the communication channel must be established, or an alternating current (AC) power outlet arranged for command and control equipment. To reduce the negative impact of blown snow, it is recommended to perform a take-off from a natural or artificial object standing at a certain height and a reasonable distance from the snow. Adapting to a different temperature (e.g., when UAS is taken indoor or outdoor) is recommended to be performed slowly, in a lengthy period of time and using a buffer zone. Some of these infrastructure elements may not be available in the Arctic fields, or there may be no infrastructure available at all [85]. This challenge may be addressed temporally with a mission-specific infrastructure set that may be deployed for the UAS mission [86].

Just-in-time/dynamic data supply has crucial importance for data-critical missions and autonomous assisted navigation [41],[49]. The full-duplex C2 communications with GCS may have different requirements for the latency depending on the nature of the UAS mission, while the reliability of the communication should not be compromised [57], [60]. This challenge is also relevant to data that is to be supplied by services provisioned through UAS Traffic Management (UTM) systems.

Low temperatures are among the weather physics challenges [77] that is a critical factor affecting the performance of UA [58]. Most of the consumer-grade UAs are certified to operate in a temperature range above 0 °C, and some are above -10 °C. Industry-grade UAs may be certified to operate in the temperature range above -20 °C. The biggest negative impact of a low temperature is on battery life [87][88]. Also, sudden voltage drops may be expected (typical for Li-Po types of batteries) [85] and even voltage loss – in case of change of the battery charge that is beyond the range controlled by an "intelligent" battery control circuit or the battery does not have that kind of circuit. The high operational performance of UA that requires high current drains the battery much faster at lower temperatures comparing to the same performance within the specified temperature range above 0 °C. In the Arctic, the temperature may drop lower than -50 °C. At that low, the temperature may affect mechanical properties of solid parts – those may become fragile; viscosity of liquids and lubricants – they may become more solid and stop supply or increase friction; and electrical properties of electronics – that may disbalance controls circuits and take some elements out of working range. Some of these challenges may be addressed with the use of nanomaterials [78],[79],[80],[81]. Low temperature-related impacts on battery life and operation can be somewhat mitigated by using self-heating smart batteries. Pre-flight, the batteries should be pre-heated to around 10 °C [85] and kept thermally insulated during flight preparations [88]. Many manufacturers also discourage the users from charging the batteries in temperatures below 5 °C. During the flight, temperatures can be maintained by using insulation [88] or chemical heat pads if the batteries are exposed to the elements.

Low-carbon operations are relevant to optimising the energy expenditure [45],[46], the flight path optimisation [45], [89], more efficient communications [61], [90], and the use of renewable energy sources [91],[92],[93].

Navigation systems satellite-based may be altered or not always be available at high north latitude. Harsh weather conditions can aggravate the situation. A magnetic compass of UA may be disoriented and require frequent recalibration. A gyroscopic compass may not be portable enough for a lightweight UA, and it may also be compromised. Compass problems conditioned by a shift of Magnetic North Pole versus the Geographic North Pole, terrestrial magnetic distribution in the Arctic and magnetic aberrations (also relevant to solar activity). A lack of precise location has a direct negative impact on an automated routing and assisted control, but also on the outcome of UAS mission or quality of gathered data, for example, in the case of image co-registering. Some of these challenges may be addressed with a variety of technology advances [29],[32],[48],[70],[94],[95] and combined with geofencing technologies enhanced with satellite remote sensing [96].

The *payload* is a combination of different technological design and mission-specific factors [97], [98], [99]. In specific cases of UAS applications, several additional considerations have to be taken into account while developing, e.g. transportation of vaccines require meeting the infrastructure requirements, transportation container design, time and vibration threshold, as well as relevant to logistics economic consideration in general [100].

Power source: modern power technologies such as solar [92] or fuel cell [101] may be supplemented with energy scavenging technologies [91]. The combination of several power sources results in hybrid engines [102],[103], which are designed to improve efficiency and reliability, while the internal combustion engines are still used [103].

Rain, mist, and fog are among the weather physics challenges [77] that negatively affect the flying performance of UA, its battery life, and communication abilities. While rain brings masses of water and mist brings moisture, fog may cause rapid moistening and water condensation. Water or moisture may accumulate and enter the electric circuits and electronic elements. Especially reach of airborne dust particles and other impurities, such as salt, that kind of moisture may be a reason for future corrosion and short-circuits, and therefore negatively affect the reliability of UA. Wet air and drops of water on a lens distort or make unusable UA sensors using optics. Some of these challenges may be addressed with, e.g., sophisticated ice detection, protection, and de-icing technologies [78],[79],[80],[81],[82].

Rapid temperature changes are among the weather physics challenges [77]. The rapid temperature drop may cause to UA similar consequences as rain, mist, and fog do. That may be addressed with similar technology advances [78],[79],[80],[81].

Safety is one of the key technological challenges [104],[105]. Variety safety-relevant aspects are investigated and addressed [53]. UAS provide great potential in improving public safety, e.g. in search and rescue, disaster assessment and response, hazard monitoring [106], but there are obvious concerns regarding, e.g. aviation safety and malicious use of UAS [104].

Security is another key technology consideration that may be addressed in a variety of ways [49], [89], [104], [107], [108]. Possible security threats include, e.g., jamming or spoofing of the localisation data or UAS transmissions, manipulation of captured footage, injection of falsified sensor data, malicious software, denial-of-service (DoS) attacks, and GCS control signals jamming or spoofing [107]. There have also been concerns of possible data capture and transmission back to the UAS manufacturer or a 3rd party, resulting in the blacklisting of certain manufacturers from governmental applications in, e.g. the United States. However, independent audits have not validated the concerns about unwanted data transmissions, although certain vulnerabilities exist [109].

Snow is one of the weather physics challenges [77]. Due to its nature, snow negatively affects the flying performance of UA, its battery life, communication abilities and reception of satellite signals just similarly as in the case of rain. Light snow may not stack on UA surface during the flight but may before the land-off and after the landing. Blowing snow may bring stacking snowflakes. Heavy snow due to a higher density of snowfall and blizzards due to a higher speed and multidirectional snow movement have more negative impacts, and snowflakes more likely stack on UA surface during the flight. Freezing rain has a stronger effect than just rain or snow since its drops immediately crystalise when they hit any surface of UA, and ice formation may grow thick. Wet snow or sleet immediately brings an additional negative impact associated with water and moisture as well as any other melting snow does. Any snowfall negatively affects the performance of UA sensors equipped with optics. Partially, this challenge may be addressed with technology advances similar to those addressing icing-relevant challenges [78],[79],[80],[81].

Storm and hailstorm bring an extreme combination of weather-related challenges that often exceed the technical ability of the UA. The heavier and bigger UAs with powerful engines and excellent aerodynamics may withstand storms to a certain degree, but hailstorms bring extra factors of falling icy hails. The flight-assistive automatic may inform a remote pilot of UA entering the storm area and offer the opportunity to return rapidly to the home base or the predefined point.

Technical malfunctioning may be very diverse [49],[54], in all varieties, from power source failures through computing or communication malfunctions and to the UA remote pilot control interface crash. The severity of technical malfunctions can be partly mitigated by increasing the redundancy of mission-critical components and control surfaces [54].

Temperature crossing 0°C is one of the weather physics challenges [77]. The temperature change from above 0 °C to below or the opposite way may cause accumulation of moisture and ice inside and on an outer surface of UA. Harsh weather conditions multiply the accumulation effect. That all may result in problems associated with poor battery performance or its failure, electronic failure, distortions of optics, and the like, which are results of conditions described before in this section. Similarly, that may be addressed with technology advances preventing icing [78],[79],[80],[81].

Time constraints are affected by take-off and landing time and speed of UAS. The main associated challenges are relevant to battery technologies, payload, and fuel type. When UASs are utilised in life-critical applications, time constraints are among the crucial factor of mission success [110], [111], [112], [113].

UAS Traffic Management (UTM) systems [56], [114], [115] raise multiple technological challenges relevant to communications, computing capacity, control interfaces, infrastructure requirements, just-in-time/dynamic data supply, safety, security, technical malfunctioning and time constraints [116].

Vertical Take-off and Landing (VTOL) features are usually not designed for operations in harsh environments and a moving home point, such as a boat or a ship, an iceberg, or a floating ice floe. Nevertheless, those are not rare operational conditions in the Arctic. The current technology development allows achieving quite challenging cases, e.g., take off from docking stations [117] or landing on a moving platform [118].

The *weight of UAS and auxiliary equipment* required for a mission may be important. Sometimes the mission must be performed by one remote pilot only. Therefore, the entire set of equipment must be lightweight and portable enough to be carried or moved by one person. On the other hand, too lightweight UA may not have enough capacity to withstand the power of wind and not being blown away. Industry-grade UAS sometimes require a team that deploys a launching base and operates the mission. A reasonable balance of equipment mobility should not require having an extra team member in addition to the operational team. Essentially, the weight of empty UA itself is a part of take-off mass and therefore is in relevance to the operational time and payload. This challenge may be positively affected by novel constructive materials such as carbon nanotubes [78].

Wind shear and whirlwind are yet another natural phenomenon [77] that bring an extreme combination of weather-related challenges [58] that may exceed the technical ability of the UA. A sophisticated flight-assistive automatic may be programmed to detect abnormal cases of wind movement and further perform the corrective actions while maintaining the set altitude.

B. Operational challenges

Operational challenges are those that may be addressed with human actions, predictive or corrective. Some problems or risks brought by the operational challenges may be reduced or excluded by access to information content and proper awareness. Some operational challenges (e.g., legislative or weather-related) are not possible to overcome and therefore, they must be taken into consideration at planning and operational phases. The weather-related operational challenges may have a crucial impact on the UA mission. Excellence in technology and UAS design may reduce the negative affection of weather factors, but it is not possible to eliminate those entirely. Alternative plans, risk avoidance, rescheduling and other mitigation activities may help to reduce the negative affection, though. To match with technological challenges and for the sake of specific operational practices to be discovered in the future – that may help to reduce or eliminate some of the weather-related challenges, all of those are listed separately even though currently known responses to many of those challenges are the same. The overview of operational challenges presented in alphabetical order is following [25][26].

AI operational challenges are relevant to limitations of AI-enhanced autonomous and semi-autonomous automation and flight assistance that should help to reduce the cognitive workload of remote pilots [119] as well as ethical dilemmas that sometimes are not even possible to be resolved by humans, such as choosing whom to harm if no other option is available [33].

Best practices that are technology-driven have already been researched for several application domains, and some of the best practices share operational aspects too. The application domains include environmental monitoring [28],[120], forestry applications [30],[121], wildlife monitoring [36], disaster management [62], hydrology [93], fishery science [122], radiometry [123], soil carbon mapping [124].

BVLOS may require the authorisation of the mission, UAS certification and a subject of UTM systems. The recently published UAS regulations in Europe categorise such missions as a specific or certified category [2],[3]. The rigid guidelines restricting BVLOS UAS missions in different countries may need to be revised or clarified [125].

Changing the density of the air to be smaller with higher altitude is well known by UA remote pilots as reducing the flight time by engaging more aggressively the UA engines to maintain the required speed and altitude [126]. The falling of UA into the air pockets may sometimes be observed visually. The front of two different atmospheric pressure areas is not possible to be recognised visually, while the information about the movement of an area with different densities may be obtained from the weather forecast.

Communications play an important role, and their failure may cause severe consequences to the UA mission. The possible negative impact may be reduced when possible problems are known or anticipated and appropriate solutions are planned in advance [60]. In case of unexpected occurrences in the field of operations, the corrective actions may be quite challenging [39].

Control interfaces may help eliminate human limitations such as slow reaction compared to a real-time control system, inability to pay attention to several objects under control [127], and the like. Modern concepts, such as Cognitive Human-Machine Interfaces and Interactions (CHMI2) [128], bring remote pilots' practices to a new level but may require additional training.

Coordination with professional operations (e.g. search and rescue, military, police, medical, etc.) is required for harm and hampering-free missions [129]. In some cases, the co-involvement may be achieved (e.g., in case of search and rescue and backcountry medical response [130]) under conditions of technical readiness of UA, qualified operator, compliance with policies and regulations and whenever needed – interoperability with or integration into the professional information system, including UTM.

Emotional aspects affect the remote pilots, the supporting team, and the other actors of UAS missions, including the object of the mission, e.g., the victim to whom the life-critical UAS mission is aimed [113]. The personal quality of remote pilots and their experience help them withstand the influencing factors. Inter-communications and support for decision making may also be helpful to all the actors of the mission, even in the case of automated missions [113].

Ethics and privacy considerations are already in the focus of legislative regulations in different countries but are still to be researched further [125]. Heightened privacy considerations, including data protection, concerning both the society members and remote pilots, are a subject for the general public and policymakers [129].

Extreme light conditions may not affect UA backed up with a multi-sensor vision. But the remote pilots and the supporting team may require auxiliary light sources or direct sunlight protection. It is recommended to consult with the weather forecast [77].

Following guidelines and professional codes of practice is a high goal but achieving that may still take quite a time [131]. Consulting existing guidelines and professional codes of practice should be essential for all the stakeholders and actors of UAS operations [129].

Formal procedures, e.g., for operation and maintenance [34], may provide more streamlined experiences with a smaller probability for errors. As well as guidelines and professional codes [131], those procedures may still not be formalised in the nearest time. Some effort towards formalisation has already been taken [3].

Freezing rain and ice fog are some of the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Geographical irregularities, such as cliffs and crevices, have a fixed position, while piles of ice and icebergs are moving obstacles. All of them, though, may complicate the selection of the home point, the mobility of remote pilots, or UA flight. Operating UA at a low altitude above the open water with floating ice floes or during the ice breaks may bring such unexpected obstacles as suddenly pushed up ice floe. Possible blind areas due to geographical formations may prevent communications between the remote pilots and UA. It is recommended to be aware of local geographical irregularities and prepared for corrective actions.

Heavy and gusty wind is one of the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Heavy clouds are among the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Human factors are often more critical to the success of a mission than technical excellence. Among many others, the factors include the level of competence, the sum of experience, the degree of understanding UAS along with onboard and auxiliary equipment and their technical abilities and limitations, and ability to proact or react to changing circumstances. The factors may not be predicted, but in the case of appearance, their negative impact may be reduced with classical approaches for human-robot interactions [67] and preventive awareness [66].

Human responses, public and personal, may vary significantly. Negative psychological and physiological human responses to UAs still require more detailed research [129]. It is recommended to anticipate or be aware of possible negative responses, and in some cases, the decision is between continuing the UA mission or cancelling it [108],[132].

Human rights should not be violated by any of the UAS missions, but the general public has a lot of concerns conditioned by sometimes unethical applications of UAS [133]. Avoidance of erosion of human rights is to be considered at the entire process of UAS operations from the planning stages to the mission outcome processing [129].

Infrastructure requirements may not be achievable in certain geographical areas or might be too high due to the demand for specific UAS missions, e.g., duration of the expedition [134]. The first type of cases may require engaging additional technological solutions, e.g., non-GPS navigation or deployment of additional equipment, e.g., a portable base station. Organising the UAS mission in the wild may require compromises between the required and the available infrastructure, and therefore a more thorough mission planning is needed. For this type of case, it is recommended to conduct a cost-benefit analysis to evaluate UAS applications' effectiveness [125].

Insufficient qualification of remote pilots may not be a reason for mission failure but may bring unwanted risks. Therefore for some specific missions, additional training, the official certification of remote pilots is required [2].

Just-in-time/dynamic data supply is not the challenge itself. The challenge is when the communication channel has been compromised, and the expected data exchange has fallen [41]. These kinds of cases may be addressed with negative scenario planning.

Lack of supply may have a dramatic impact on the UAS mission. During the mission, it is possible to run out of energy (e.g., battery charge or fuel), spare parts and tools, life support for the team (e.g., food or water), and other supply due to a variety of reasons such as the wrong estimate of required quantity/amount or need to have, broken equipment, possibilities to lose equipment, etc. The nearest source of supply may be located unreachably far, and transportation is difficult to impossible to arrange. Such a situation may lead to a cancellation of the mission and even calling a rescue. The lack of supply may appear during local missions but have a higher impact during a long-time expedition [41],[134]. The probability to appear may be reduced by careful planning and availability of spare equipment and a reserve of supply.

Laws, policies, and regulations are countries or geographic area dependent. Legislative materials may outline restrictions and prohibitions, describe operational practices, and inform of required processes, licenses, and permissions. Among those to be considered are challenges relevant to generic or Open applications of UAS and relevant to the Specific and Certified operations. For example, health or medical applications of UAS [125] may require certification of mission-specific equipment.

Low temperatures are among the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Navigation systems may be impacted by heavy clouds (satellite) or extreme light conditions (visual sensor-based). Missions performed during the daytime in cloud-free conditions are recommended [135]. Other impact factors are presented above [25], and those that are specified by mission requirements may demand more sophisticated UA technologies utilising multi-sensor non-satellite positioning.

The *payload* of the UA should be known at the planning stage. The weight of cargo would not exceed the specified payload capacity. Performing the UA operation with the excess of the payload may cause mission failure and safety threats. The general public has sometimes been concerned [108] about the nature of the payload and the appearance of heavy cargo transported by UA in relatively close proximity.

Planning and following the plan is often challenging in case of any type of human activity. In extreme rapidly changing conditions, following the plan strictly is not always feasible and safe. Sometimes advancing or preventive action or even cancellation of a mission is necessary. The best plan, though, is the one where all the possible changes are anticipated and considered. Following the plan is essential, unless there is a strong need to change to the backup plan or to act proactively [136].

Power source shortage may appear during a long-time expedition along with a shortage of other supplies [41],[134], and mitigation actions are similar.

Processes-relevant challenges [34], [108],[131] often occur when generic, typical, or normalised processes are not sufficient enough, and a deviation or even breakthrough is required. Such situations may be passively adopted or actively developed. An example of the first is the need to use extra solid gloves to control UA on a frosty day. The second is essential for research. For example, a commercial off-the-shelf (COTS) consumer-grade UAS is used for non-trivial tasks that it has not been designed to be used for. That may require additional equipment or improvement of UAS itself or the rationalised operational process. These types of challenges are usually known in advance and may be considered during the planning phase.

Rain, mist and fog are among the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Rapid temperature changes are among the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

The *security breach* is one of the serious challenges that may lead to lost data and/or control of UA and make the mission compromised, e.g., the flight may be re-routed [125]. Properly addressed security challenges may help to reduce the risk of a security breach.

Short flight time is one of the most important operational challenges. In the Arctic, territories are large, but at the same time, many places are difficult to reach. The flight time of UA may be affected negatively by harsh and even more by extreme weather conditions. Therefore, UA missions must be well-planned, and during the mission, operators should provide responsive and even proactive control. Also, this challenge is relevant to the availability of supply [42],[105].

Snow is one of the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Storm and hailstorm may make it impossible to perform the UA mission. It is recommended to consult with the weather forecast [77]. The UA may be set to the automated rapid return to the home base or the predefined point, or that operation may be triggered by the remote pilots.

Technical malfunctioning may not be resolvable during the mission [125], while the negative impact may be reduced by a fast and correct response of the remote pilots. It is possible to assume that conducting the UA mission within the range of technical specifications of the UAS would not cause the additional risk of technical malfunctioning. When the corresponding safety and technological challenges are properly addressed, the negative impact of technical malfunctioning may be reduced or entirely eliminated, e.g., by redundant functionality. When the UA is not able to return to the departure point, the search missions may be more effective if the remote pilot and supporting team are prepared in advance and backed up with positioning technologies. These kinds of cases may occur when, e.g., as a result of technical malfunctioning, the UA parachute is engaged, or the UA is blown out of operating range by the wind.

Temperature crossing 0°C is one of the weather-related challenges that can impact the success of a UA mission [125]. It is recommended to consult with the weather forecast [77].

Time constraints are an important consideration in rapidly changing weather conditions since those may simply make it impossible to perform the planned mission. Life-critical missions require pro-active planning and fast reaction to the fast-changing situation. For example, optimal placement of UASs to cover the operation area, optimal routing and help with decision-making may significantly help to cope with time constraints [110], [111],[112],[113].

UTM associated challenges may appear when dynamically updated information due to newly discovered circumstances is such that may require re-routing or may affect the UAS mission dramatically. Then the involvement of the entire support team may be needed for rapid decision making [137].

VTOL is yet another UAS operation, but it may bring certain requirements, especially in the Nordic conditions. For example, a launching pad or base may be required, or the launch can be performed from a docking station [117].

The *weight of UAS and auxiliary equipment* is not only important when the remote pilot and the supporting team moves to remotely located areas to deploy the temporal home base. For some of the specific UAS missions, it is recommended to conduct a cost-benefit analysis to evaluate the effectiveness of UAS applications [125].

Wild animals may be disturbed by UA and expose a wide range of emotions from internal stress to angriness [138], [139] that may result in their attack [140], especially if they consider it as a threat to their offspring. Also, the UA may be accidentally damaged by fighting animals. It is recommended to get acquainted with the presence of wildlife in the area of the UAS mission and minimise the possible negative impact [138], [139].

Wind shear and whirlwind are often so rapid that a remote pilot cannot respond to the sudden change in UA flight trajectory or excessive vibration. In some cases, it is possible to respond with corrective action. That depends on the ability of the remote pilot, which can be developed as a result of training. The corrective actions of flight-assistive automatic may be very efficient to help.

III. Discussion

The European Union Aviation Safety Agency (EASA) published Easy Access Rules for Unmanned Aircraft Systems (UAS) [141] that contains the rules and procedures for the operation of unmanned aircraft (UA) adapted for better understanding of recent EU regulations (EU 2019/945 [2] and EU 2019/947 [3]) by the general public. In every UAS operation, it is necessary to evaluate the environmental and weather conditions beforehand and, in some specialised cases - even acquire advanced weather information. Many UAS technology manufacturers need to take into consideration the different kinds of weather factors that affect the UAS hardware. Most notably, Arctic or Nordic specific conditions are not yet taken into consideration at all.

More research is needed to investigate the Arctic challenges and their particularities further. Every technological challenge may be addressed in a variety of ways. Those ways are worthy of dedicated research. For example, such technological challenges as safety may be addressed by a variety of safety features, including a parachute system or introducing a backup in electronics or propulsion system to enhance safety. While the UAS physical security is well taken into account, the cyber security aspect breach may eliminate the excellence of all safety systems and cause unwanted consequences. The holistic view at the UAS as technology artefact exposed to the broad set of challenges may help understanding the common causes of those and interrelationships between them, which in its turn may help to advance technological elements is a way that the design of the entire artefact would achieve the higher degree of robustness and resilience to severe weather conditions.

More systematic research on operational best practices is needed, as well as communication with the general public. Managing the operational challenges is in line with the development of UAS and its supportive infrastructure technologies. Global challenges to humanity, such as the COVID-19 pandemic, accelerate the applications of UAS [142]. To have a good match of the technological progress with labour forces for the benefits of society, contribution to the professional development of the remote pilots is needed as well. That includes formal education, acquiring and sharing experiences, gathering and processing operational data, and raising public awareness of the benefits that UAS applications may bring. Supportive regulations and positive perception of the general public will obviously have a positive impact too.

To address some of the operational challenges, raise awareness, reduce possible risks and simplify planning, the dedicated remote pilots' handbooks were developed [143] [144]. Also, best practices to minimise the UA disturbance to wildlife are published as basic guides [145].

Many different documents and guidelines are still under development for UAS operations. The formalised approach has been taken by the American Society for Testing and Materials (ASTM) Committee that started working on New Practice for General Operations Manual for Professional Operator of Light Unmanned Aircraft Systems (UAS) [146]. In Europe, Joint Authorities for Rulemaking of Unmanned Systems (JARUS) developed guidelines on Specific Operations Risk Assessment (SORA) [147].

IV. Conclusion

Unmanned Aircraft Systems (UAS) and their recent advances offer great potential for both commercial and non-commercial applications. However, it has also raised both regulatory issues as well as technical/operational challenges. In this article, all the technical and operational challenges presented are typical to applications of UAS in the Nordic harsh weather conditions from very hot to winter freezing with rain, snow and all the water elements between them. Both the generic UAS challenges and considerations are overviewed included references.

Nordic weather is the challenge for UAS, and that must consider when pilots are operating drones as safely as possible. Environmental conditions not only associated with the weather but also with geographical and other environmental particularities bring a broad range of challenges that have a strong influence on the safety of UAS operations. Safety UAS operation needs the understanding of weather parameters but also investments in high-quality UA to avoid accidents. The possible UA crash is not only associated with the damage of property or wildlife but may cause a risk to the lives of people. In addition, the reputation of UAS operators and UAS vendors suffers.

In future research, attention must focus on comparing the severity of external factors on UAS operation with other research results, such as those conducted by MIT Lincoln Laboratory [58] and learning how to solve the challenges listed in the article. Also, sharing knowledge of the impact of Nordic conditions is needed by communicating with stakeholders and official bodies providing safety guidance and training materials, e.g. [148] and by educating remote pilots employed by UAS operators, for example, as a part of the training provided by the DroneMaster project.

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