UAV Arctic Challenges and the First Step: Printed Temperature Sensor

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***Abstract*—This paper presents an extensive collection of technical and operational challenges associated with Unmanned Aerial Vehicles (UAV) operations in the Arctic. Some of the challenges are valid for Antarctic, severe, winter, and near-winter weather conditions. The collection of challenges was developed by analyses of a great number of practical applications of UAVs. The tiny step towards the technological excellence making the Arctic operations of UAV approachable is also presented in the paper. That is a printed temperature sensor able to work at low temperatures up-to -40 °C. The results of the sensor testing are given.**

I. INTRODUCTION

In this work, all lightweight aircrafts typically referred to as Unmanned Aerial Vehicles (UAV), Unmanned Aerial Systems (UAS), Remotely-piloted Aircraft Systems (RPAS) [1] and drones will be referred to as UAVs.

The history of applying UAVs in the Arctic has started with military applications and gradually spread civil [1], [2]. Non-military use of UAVs (e.g. for evaluating a thickness of sea ice, roughness and over ice temperature of water and land, a variety of observations) counts more than two decades and begins from the application of aerosondes [3]. Also, blimps, balloons and kites are used for environmental and coastal remote sensing [4]. At the beginning of this century, it has already been clear that utilisation of UAVs is relatively less expensive than utilisation of manned aviation, submarines or satellite systems to accomplish the same missions [1], and even more precise and efficient than the last ones [3].

These days the application of UAVs in cold and harsh environments such as the Arctic and Antarctic are very broad. It include remote sensing in fluvial environments [1], wildlife [5] and airborne [6] monitoring and population ecology [7], river ice [8] and sea ice movement tracking [9] and 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, e.g. [18], and many others.

In addition to the professional application of UAVs for research, business and military purposes, consumer's applications will also appear more and more with the rapidly increasing in the Arctic tourism [19]. Moreover, there is a spreading area of non-commercial application of UAVs for the benefits of society. With the involvement of private individuals, academic researchers, journalists, non-governmental organisations (NGOs) and sometimes public services and commercial structures, UAVs may be used for humanitarian aid, environmental protection, emergency services, responsible journalism and activism [20].

All the applications of UAVs bring a great number of challenges. Some of those challenges may be addressed with a more sophisticated design of UAV electronics. In general, and particularly concerning operational requirements, modern printed electronics technologies can bring extra value with their traditional benefits such as physical flexibility, power efficiency and low-cost production [21].

The rest of this paper has the following structure. A collection of technical and operational challenges that were gathered as a result of extensive analyses of practical applications of UAVs is presented in Section II. In Section III, the research subject is proposed, and its selection is justified. The proposed subject is a tiny part of a complicated design of the modern UAV and just the first one in a series of subjects that are planned to be researched for the Arctic applications. A short overview of printed temperature sensors is given in Section IV. Results of the temperature sensor testing are presented in Section V. Concluding remarks are given in Section VI.

II. ARCTIC CHALLENGES

A. *Technical challenges*

Technical challenges are those that may be addressed, and their impact reduced or eliminated with the development of technologies, improved design or functionality of UAV, 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 UAV mission).

Heavy and gusty wind negatively affects control of UAV and its battery life. The wind having a speed about the speed of UAV or higher may compromise a mission and make impossible a return of UAV by blowing it away. At higher altitudes, the wind speed may be higher than at lower altitudes. It is very challenging to develop an automated piloting algorithm to compensate for heavy and gusty wind and maintain a plane position of UAV with the minimum course fluctuation.

Rain and fog negatively affect flying performance of UAV, its battery life, and communication abilities. While rain brings masses of water and moisture, fog may cause 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 UAV. Wet air and drops of water on a lens distort or make unusable UAV sensors using optics.

Heavy clouds negatively affect satellite signal reception, required for positioning systems, such as Global Positioning System (GPS). Also, the clouds may make difficult or impossible visual contact with UAV.

Dust or solid particle clouds blew from the ground in the result of take-off and landing or brought with masses of air, may temporally alter or disable visual contact and communication with UAV and performance of its optics-equipped sensors. Entering the small particles to mechanical parts of UAV may bring extra friction and alter mechanical performance. UAV 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 and communication.

Solid particle and liquid ingress protection determine two important yet basic properties of environment tolerance of UAV. The levels of protection are known as IP Codes or International Protection Marking and classified by IEC 60529 standard [22]. It is important though that not only UAV 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 UAV. For example, heavy rain or dust storm may not break the seal of UAV but jeopardise its operation.

Temperature is a critical factor affecting the performance of UAV. Most of the consumer-grade UAVs are certified to operate in a temperature range above 0 °C, and some are above -10 °C. Industry-grade UAVs may be certified to operate in the temperature range above -20 °C. The biggest negative impact of a low temperature is on battery life. Also, sudden voltage drops may be expected (typical for Li-Po types of batteries) 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. High operational performance of UAV 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.

Ice fog consists of instantaneously crystallizing water particles and may cause icing of contacts – that changes electrical properties or breaks the conductivity; forming icy masses on propellers and wings – that worsen aerodynamic properties; or a body of UAV – that affects negatively to an overall balance of UAV in the air and may freeze control surfaces.

Due to its nature, snow negatively affects the flying performance of UAV, its battery life, communication abilities and reception of satellite signals just similarly as in the case of rain. Light snow may not stack on UAV 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 blizzard due to a higher speed and multidirectional snow movement, have more negative impacts and snowflakes more likely stack on UAV 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 UAV 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 snow affects negatively the performance of UAV sensors equipped with optics.

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 UAV. 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.

Certain infrastructure is required or recommended for UAV operations. For example, the communication channel must be established, or alternating current (AC) power outlet arranged. 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 snow. Adapting to a different temperature (e.g. when UAV is taken indoor or outdoor) is recommended be performed slow, in a lengthy period of time and using a buffer zone. Some elements of infrastructure may not be available in the Arctic fields, or no infrastructure available at all.

The weight of UAV and auxiliary equipment required for a mission may be important. Sometimes the mission must be performed by one UAV operator 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 UAV may not have enough capacity to withstand the power of wind and not being blown away. Industry-grade drones 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 empty weight of UAV itself is in relevance to the operational time and payload.

Internet access may be absent, and even the satellite Internet connection may not always be operational, 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 with ground control station (GCS). In the case of radio communication, it may be affected by magnetic storms. Some radio frequency bands may be a subject of licensing or reserved.

Innovations relevant to UAV 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.

Satellite-based navigation may be interrupted or not always available at high latitudes, and harsh weather conditions may make it even worse. A magnetic compass of UAV may be disoriented and require frequent recalibration. Gyroscopic compass may not be portable enough for any UAV and also may 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 UAV mission or quality of gathered data, for example in a case of image co-registering.

Vertical Take-off and Landing (VTOL) features of UAVs 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 rear operational conditions in the Arctic.

Battery technologies develop over the years, but still prone to charge loss and voltage drop and loss under low temperatures. Battery capacity, keeping temperature conditions alternative energy sources and energy harvesting are matters of cutting-edge R&D&I activities at these days.

The current state of the art microprocessors is 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 unilateral computation may be beneficial.

Extreme light 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 to photo and video equipment used with UAVs, particularly – to their exposure and white balance properties and abilities.

A vast number of sophisticated assistive and mission-specific sensors for UAVs are developed worldwide, and yet more to come.

Modern UAV body materials, main construction and moving parts are produced using composites, which are very strong, stiff and durable and at the same time lightweight (e.g. all-carbon-fibre). Newly developed materials have high chemical resistance and keep their properties in a wide range of temperatures. Carbon nanotubes may be used to build electric-powered coating that prevents icing of UAV surface. Composite additive-enhanced materials may be 3D printed [23].

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 for 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.

Weather conditions and low temperatures are the key operational challenges. A collection of technical challenges is described above in this section, and many of those are related to the weather conditions. Excellence in technology and design may reduce the negative affection of weather factors, but it is not possible yet to anticipate that those will be excluded entirely. Careful planning of UAV missions may also reduce the impact of weather. Alternative plans, risk avoidance and rescheduling, may help to succeed in typical to the Arctic rapid weather changes.

Short flying time is one of the most important operational challenges. In the Arctic, territories are hugely large, but at the same time, many places are difficult to reach. Harsh weather conditions shorten the flying time. Therefore, UAV missions must be well-planned, and operators provide responsive and even proactive control.

A lack of supply may have a dramatic impact on the UAV mission. During the mission it is possible to run out of energy (e.g. electricity), 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 wrong estimate of required quantity/amount or need to have, broken equipment, several possibilities to lose, 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.

Laws, policies and regulations are countries or geographic area-dependent. Legislative materials may outline restrictions and prohibitions, describe operational practices and inform of required licenses and permissions.

Processes-relevant challenges 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. Example of the first is a need to use extra solid gloves to control UAV on a frosty day. The second is essential for research. For example, a commercial off-the-shelf (COTS) consumer-grade UAV is used for non-trivial tasks that it has not been designed to be used for. That may require additional equipment or improvement of UAV itself or the rationalised operational process.

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 and sum of experience, the degree of understanding UAV along with onboard and auxiliary equipment and their technical abilities and limitations, and ability to proact or react on changing circumstances.

Planning and following the plan is always challenging for any type of human activities. 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. The best plan though is the one where all the possible changes are planned.

Geographical irregularities, such as cliffs and crevices, are having 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 UAV operator, or UAV flight. Operating UAV at a low altitude above the open water with floating ice floes or during the ice breaks may bring such unexpected obstacle as suddenly pushed up ice floe.

Wild animals may attack a near flying UAV if they consider it as a treat to their children. Also, UAV may be accidentally damaged by fighting animals.

Those are not all the operational challenges. A collection of implicit or indirect challenges includes the following [20]. Negative psychological and physiological human responses to drones still require more detailed research. Heightened privacy considerations including data protection, concerning both, the society members and UAV operators, are a subject for the general public and policymakers. Avoidance of erosion of human rights is to be considered at the entire process of UAV operations from the planning stages to the mission outcome processing. Coordination with professional operations (e.g. rescue) is required for harm and hampering free missions. Consulting existing guidelines and professional codes of practice should be essential for all the stakeholders and actors of UAVs' operations. [20].

To address the operational challenges, raise awareness, reduce possible risks and simplify planning, a dedicated UAV operator's handbooks were developed [24] [25]. Also, best practices to minimise UAVs' disturbance to wildlife are published [26].

III. PROPOSED SUBJECT

In this work, the reference is technical challenges relevant to UAV electronics. Using printed technologies to build an electric vehicle is a growing trend [27]. Using printed electronics in aerospace domain bring many advantages, especially in case of their applications in lightweight battery-powered UAVs [28].

What is very important, due to several factors such as flexible structure, corrosion resistance etc., printed electronics has higher reliability compared to traditional electronics. Advantageously, printed components can be relatively thin – down to tens of µm, and therefore they have a small mass. Conveniently, printed materials can be flexible, bendable, manufactured to any shape and size and even and even transparent if needed. One more benefit is related to a better electric property (e.g. high conductivity materials, low losses on contacts) of the printed electronics that has a direct positive effect on low energy consumption. The combination of printed electronic benefits leads to easier design, less physical volume and lower maintenance requirements [3].

Within the current trend towards to low-carbon and green economy, it is possible to use environmentally friendly materials to produce the printed sensors. Manufacturing of the component can be done using high output roll-to-roll manufacturing, which in its turn decreases the cost per component.

The focus of this research is on a small but important element of modern UAV electronic circuit: a temperature sensor. An additional requirement is operations in low temperatures, up to -40 °C.

Several reasons justify the availability of a temperature sensor in modern UAVs operating in cold conditions. For example, the sensor may be a part of logic that checks a condition of UAV battery or predicts a battery life by monitoring the environment temperature in order to improve the functionality of automated Return to Home (RTH) feature.

Temperature sensors are utilised for logging ambient temperature as a part of automated or post-processing calibration of spectral cameras [29] and infrared (IR) radiometers [30].

Moreover, temperature sensors are required for implementing recent enhancements and replacements [31] of traditional UAV battery technologies. Among those are solar cell [32] and fuel cell [33] [34] powered sources of energy. Fuel cell solutions for UAV operations in low-temperature environments such as Arctic climate or high altitude are not yet mature and require additional technologies to keep the cell within the specified temperature range [33], [34]. Solar cell solutions are feasible [35], and the first actual implementation has already been tested in the Arctic [36]. One of the current UAV development trends is the utilisation of energy harvesting techniques, e.g. thermal engines, also requires the availability of temperature sensors [37].

IV. PRINTED TEMPERATURE SENSORS

The temperature sensor is a key element of any system intended to be used for monitoring temperature. The behaviour of the temperature sensor might be heavily affected by extremely low temperatures due to a physical phenomenon. This paper describes the research done to find out the functionality of printed sensors in extremely low temperatures.

The simplest way of knowing the temperature is temperature indicators, which are simple, lightweight and inexpensive devices that can be used to demonstrate the temperature of the subject visually.

With a colour change indicator or small LCD/LED display these small devices provide a single visible result, an indication to confirm the temperature. They often take the form of cardboard strips/self-adhesive labels or small devices, to be placed on the product or within a shipment, and able to monitor products individually.

The limitations of temperature indicators are that the colour change processes are irreversible and so they are single-use devices. With chemical indicators, identifying a colour change is subjective and not an exact or accurate temperature reading [38].

Within the given application domain, temperature indicators have limited applicability. The result of measurement is only possible to read at a small visual distance (e.g. while UAV in small proximity from an operator, on the ground, or in hands).

Galvanic thermocouples are used to measure temperature by measurement of the small voltage formed over the junction of two metals of different Seebeck coefficients. These types of sensors are suitable when measuring relatively high temperatures, but they lack performance in low-temperature conditions [39] and therefore not suitable for utilisation of UAVs operating in cold environments. Galvanic thermocouples are also manufactured using at least two different materials which increase the complexity of manufacturing [40].

Thermistors are temperature sensitive resistors, which have a nature of changing their resistance when the temperature changes. Thermistors have very often negative temperature coefficients (NTC) which means the resistance decreases as the temperature increases. These components are called NTC thermistors. Thermistors with a positive temperature coefficient (resistance increases as the temperature increases) are called PTC thermistors.

Thermistors are simple and yet accurate, they can be used to measure wide temperature range, and they are well suitable for also measuring low temperatures. This type of temperature sensors is the most suitable for utilisation in UAVs operating in cold environments.

V. TEMPERATURE SENSOR TESTING

Temperature sensor testing was done using three different printed temperature sensors. These sensors have been found to be well performing in not so extreme temperatures [38], so that is why they were chosen for this research.

Temperature sensors are a) NTC type thermistor, manufactured on PET using screen printing, size of the component 29 x 24 x 0.1 mm., b) screen printed NTC type thermistor, size 4 x 4 x 0.21 mm. and c) PrinLab PTC type temperature sensor, size 16 x 24 x 0.15 mm.

Fig. 1. Temperature sensor a) bottom side (left image) and top side (right)

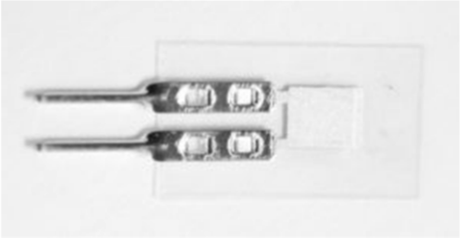

Fig. 2. Temperature sensor b)

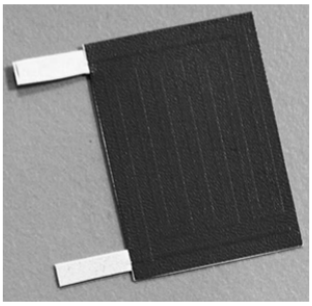

Fig. 3. Temperature sensor c)

PrinLab temperature sensors (c) are screen printed on a 150 µm PET substrate using the selected carbon blend paste. For light mechanical and environmental protection, the sensors are covered with a thin transparent dielectric layer. However, the dielectric layer does not provide perfect insulation against conductive materials such as water. An extra layer of insulation should be used in case of the possibility of conductive materials to be in contact with the sensor and also for better mechanical protection. Sensor b) is hermetically sealed and a) doesn´t have any specific protection against environmental conditions. To ensure equal conditions for performance tests all the components were sealed in a plastic bag during tests, see Fig. 4.

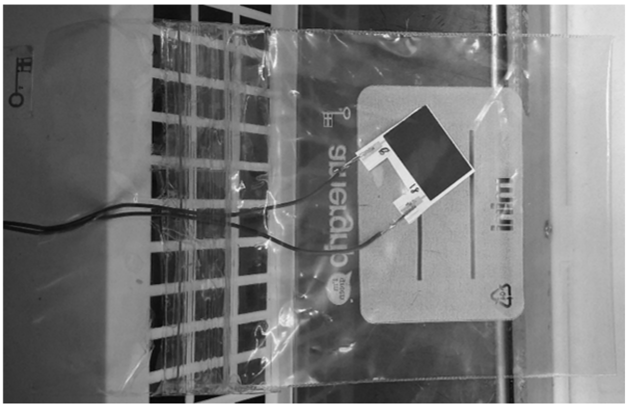

Fig. 4. Temperature sensor setup at test

Temperature sensors were tested in environmental test chamber Heraeus Vötsch HT4002 and resistance of the components was measured using Fluke 179 true RMS multimeter. The temperature of the test chamber was measured using a Fluke 50S thermometer and K-type probe.

Test range was from +20 °C to -40 °C and resistance values were taken every 5 degrees (around 0 also at +2 and -2 °C). Results of the test can be found from the table I. Note that the sensor a) and c) values are in MΩ and sensor b) in kΩ.

TABLE I. SENSOR RESISTANCE VALUES

Temp., °C	a) 1	c) 1	a) 2	b) 1	c) 2	b) 2
20	15,96	1,336	19,99	9,29	1,535	9,67
10	20,77	1,248	25,99	9,74	1,403	10,16
5	23,6	1,212	29,34	9,97	1,362	10,41
2	25,46	1,193	31,7	10,1	1,343	10,56
0	26,67	1,185	33,15	10,19	1,331	10,65
-2	28,41	1,17	35,39	10,31	1,315	10,79
-5	30,21	1,159	38,56	10,52	1,292	10,96
-10	34,97	1,133	44,28	10,78	1,266	11,26
-15	40,19	1,115	50,73	11,09	1,244	11,56
-20	46,29	1,1		11,37	1,227	11,88
-25	53,71	1,086		11,69	1,212	12,22
-30		1,074		12,01	1,198	12,55
-35		1,062		12,35	1,185	12,92
-40		1,053		12,69	1,172	13,31

Resistances at room temperature are significantly different between tested sensors. Sensor a) value at 20 °C is 16 – 20 MΩ, sensor b) 9,3 – 9,7 kΩ and sensor c) 1,3 – 1,5 MΩ.

The linearity of the components is shown in the following figures. Linear curve and R^2 value are also shown. The linearity of the components seems to be reasonable and does not prevent the component usage in low-temperature conditions.

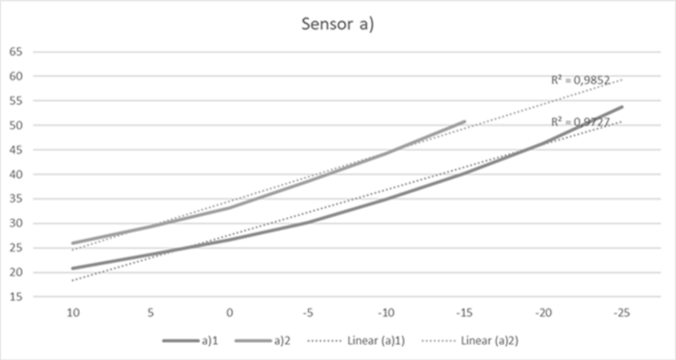

Fig. 5. Sensor a) resistance vs temperature curves

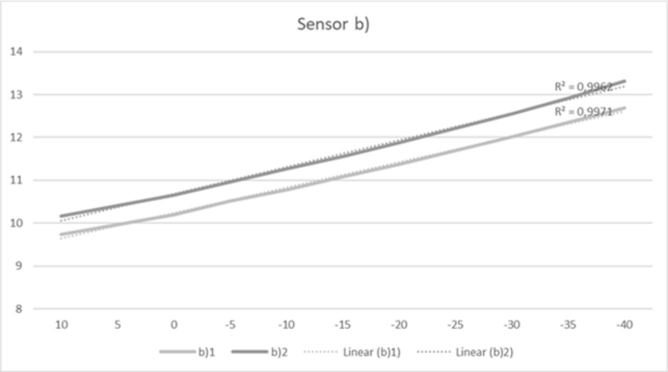

Fig. 6. Sensor b) resistance vs temperature curves

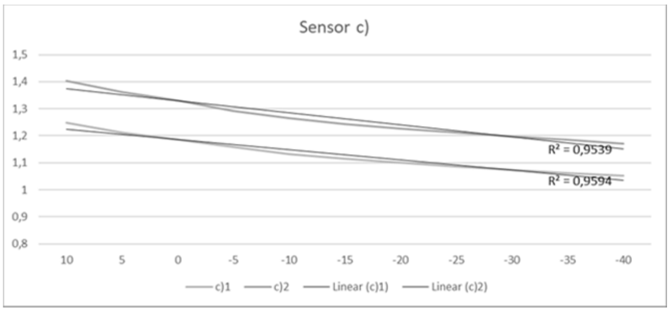

Fig. 7. Sensor c) resistance vs temperature curves

TCR (Temperature Coefficient of Resistance) of the components was measured from the range specified using the formula below:

$$\alpha = \frac{\frac{R}{Rref} - 1}{T - Tref}$$

where R = Resistance at temperature T

Rref = Resistance at 20 °C

T = Temperature in °C

Tref = 20 °C

TCR values are -0.044…-0.053 for sensor a), -0.0061…-0.0063 for sensor b) and 0.0035…0.0039 for sensor c). It should be noted that sensor a) resistance was exceeding the measurement device capability at -20 C and -30 °C, so the TCR is calculated based on the values are shown in Table I.

VI. CONCLUSION

All the technical and operational challenges presented in this paper are typical to applications of UAV in the Arctic, although some challenges are valid for Antarctic, severe, winter, and near-winter weather conditions. Moreover, the challenges are not limited to those conditions only. Many are valid for a moderate climate and even UAV operations in hot deserts.

Development of printed temperature sensor able to work at low temperatures up to -40°C is the first step in a series of research experiments contributing to advances of UAV technologies that make operations in the Arctic zone more approachable.

All the tested temperature sensors are well suitable for measuring in low-temperature conditions. As being manufactured to thin and flexible substrates, they can easily be embedded into different structures without compromising the reliability, structure integrity, weight, power, manufacturing or operational cost.

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