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Survey of Thermal Infrared Remote Sensing for Unmanned Aerial Systems

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Abstract— **As Unmanned Aerial System (UAS) technology matures, the list of potential civilian applications continues to grow substantially. Currently, the majority of applications are centered around providing optical imagery, either in real-time video or high resolution mapping. But as more sophisticated applications are desired, the limitations of simple imagery are becoming more evident, especially for precision agricultural applications. However, recent advancements in UAS based precision agriculture have demonstrated the effectiveness of including thermal infrared (TIR) cameras. In many situations, decision support indicators are evident in the TIR spectrum, whereas they are undetectable in the visible light and near-infrared spectrum. In this paper, a survey of some of the applications under development utilizing TIR imagery is presented along with implementation strategies to provide guidance for researchers wishing to add TIR imagery into their applications.**

I. INTRODUCTION

In the upcoming years, Unmanned Aerial Systems (UASs) are expected to play major roles in the domestic skies. In one study, as much as 90% of the expected UAS market is expected to belong to either agriculture or law enforcement [1]. These lofty predictions have driven the development of a boom in UAS production, but due to both technical and legislative challenges, those expectations have yet to manifest. Futuristic visions of drones delivering packages may not be reachable in the near future, but there remains several significant and realistic beneficial uses of domestic UASs. Given the wide range of system capabilities, the versatile aircraft can serve as the quintessential remote sensing platform. Armed with high resolution cameras, UASs can provide unparalleled spatial and temporal resolution at a fraction of the cost of manned aerial imagery. But to capitalize upon the benefits of small UASs to the highest degree, limiting remote sensing to visible light spectrum imagery is insufficient.

In the process of researching civilian applications for UASs, many groups have begun to move beyond the visible light and started making camera modifications to utilize the near-infrared light spectrum, enabling an even greater number of applications. The transition from the visible light spectrum to the near-infrared light spectrum often requires only minor modification to many commercially available digital cameras, making it a significantly cost effective upgrade. Many applications, such as the calculation of vegetation indices including the Normalized Difference Vegetation Index (NDVI), are enabled with a combination of visible band and near-infrared band of the light spectrum.

However, for many applications, especially in agricultural and environmental fields, the results from only the visible and near-infrared spectrum calculations have not been as promising as hypothesized. Increasingly, recommendations to evaluate other light spectrum have appeared in an effort to extract more relevant data from remote sensing strategies.

Thermal imagery, derived from the far-infrared or thermal infrared bands, has shown promise as the missing element to develop the quantifiable data critical to actionable intelligence for many applications. Unlike near-infrared imagery, thermal imagery requires a dedicated thermal imager which has slowed its adoption. As thermal imager technology has decreased both in size and weight, it has become more presentable as a viable sensor option for a remote sensing UAS. While the use of thermal imagery obtained from a UAS is not new or revolutionary, its use has primarily been for surveillance in military or law enforcement applications. Only in recent years has the impact as a scientific tool for domestic applications been fully investigated. Despite the cost and the challenges, thermal imagery can provide valuable information, most notably in agricultural applications.

The purpose of this survey paper is to highlight the number of applications enabled by the use of thermal imagery from a UAS for civilian applications and provide insight into its operation and integration. In Section II, a general overview of the thermal infrared camera system will be introduced and discussed. Section III classifies thermal infrared imagery applications into three distinct mission classifications. Challenges regarding camera calibration and mission implementation are discussed in Section IV. Concluding remarks are presented in Section V.

II. THERMAL INFRARED CAMERA SYSTEMS

Infrared light is the electromagnetic radiation with wavelengths that range from the edge of visible red (700 nm) to roughly 1mm. While the near-infrared (700 nm - 1.4 μm) and short-wave infrared (1.4 μm - 3 μm) spectrums are primarily from reflective radiation, thermal infrared (3 μm - 15 μm) is primarily composed of emitted radiation. This allows for a sensitive radiation measurement sensor to estimate the

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TABLE I

CURRENTLY AVAILABLE TIR CAMERAS

Camera	**Resolution**	**Weight**	**Output**	**Spectral Band**	**Max Frame Rate**
FLIR T450sc	320 x 240	880 g*	USB/NTSC	7.5 μm - 13.0 μm	30 Hz
FLIR A325as	320 x 240	700 g	Ethernet	7.5 μm - 13.0 μm	60 Hz
Gobi-384 (Scientific)	384 x 288	500 g*	NTSC/Ethernet/CameraLink	8.0 μm - 14.0 μm	50 Hz
ICI 7640 P-Series	640 x 480	127.6 g	USB 2.0	7.0 μm - 14.0 μm	9 Hz
InfraTec mobileIR M4	160 x 120	265 g*	NTSC/USB 2.0	8.0 μm - 14.0 μm	60 Hz
Optris PI400	382 x 288	320 g*	USB 2.0	7.5 μm - 13.0 μm	80 Hz
Pearleye LWIR	640 x 480	790 g*	CameraLink/Ethernet	8.0 μm - 14.0 μm	24 Hz
Tamarisk 640	640 x 480	121 g	NTSC/CameraLink/USB 2.0	8.0 μm - 14.0 μm	30 Hz
Tau 640	640 x 512	110 g	NTSC	7.5 μm - 13.5 μm	30 Hz
Thermal-Eye 4500AS	640 x 480	108 g	NTSC	7.0 μm - 14.0 μm	30 Hz
Thermoteknix MIRICLE 370K	640 x 480	166 g	NTSC	8.0 μm - 12.0 μm	240 Hz

*denotes TIR Camera weight includes housing and lens

kinetic surface temperature of an object by the amount of emitted radiation the object emits, isolated from any reflected radiation. The development of thermal imaging equipment and temperature estimation is a science to itself and is beyond the scope of this survey. The reader is encouraged to consult literature such as [2] for a comprehensive review.

Thermal infrared camera systems are not as diverse as other optical imaging systems, though there exists some variations, especially within resolution and output. A typical thermal imager will range in price from $2,000 to $50,000 depending on the quality and functionality. While the prices have decreased significantly over the past few years, they are still more expensive than the commercial off-the-shelf camera systems widely used in small UAS. A list of example camera systems currently available can be found in Table I. This listing is not exhaustive, though is representative of many possible solutions found through literature review and experience.

As with other optical systems, the final mission objective dictates the minimum image quality [3]. However, unlike the large assortment of digital optical equipment, thermal imagers have a much more limited range of quality. The majority of commercially available TIR cameras have a resolution of 640 pixels by 480 pixels; significantly less than commercially available off-the-shelf point and shoot cameras that have resolutions typically above 4200 pixels by 2800 pixels. As will be discussed in Section IV, this has significant effects on mission implementation strategies.

III. THERMAL INFRARED IMAGERY APPLICATIONS

While there is a multitude of UAS applications, those utilized for remote sensing operations can be classified by the level of sophistication and accuracy of the desired final goal. In this paper, UAS applications are broken down into three sets of increasing complexity: Detection Missions, Identification Missions or Analysis Missions. The applications developed around a detection mission are the simplest in terms of payload operation where the goal is to detect a target of interest. Applications developed around an identification mission often require improved optics to differentiate objects and typically require spatial referencing. Analysis missions involve further processing of the data to provide actionable information. Simply put, the three categories can be separated by asking which of the following questions is the goal of the mission.

- Detection - Is it there?
- Identification - What is it?
- Analysis - What does it mean?

Table II contains a list of TIR UAS application publications, sorted by mission type and year of publication. The majority of published research on TIR UAS applications are related to the more complex missions of identification and analysis. This, however, is not a reflection on the number of TIR UAS applications.

A. Detection

The primary motivation for the utilization of thermal imagery for UASs have historically been within the military or law enforcement applications. In these situations, thermal imagery provides a new layer of information that improves or enhances performance. Bringing this ability to civilian applications can potentially lead to the use of thermal imagery for search & rescue or firefighting applications [4].

1) Key Attributes: In both of these applications, the utilization of thermal imagery is to be able to see heat signatures without the necessity of scientific grade resolution. The payload processing complexity is significantly reduced compared to the other classifications. In these detection missions, the user (a ground control or payload operator) is tasked with the higher level decision making, relying on human expertise rather than system automation. In many of these types of sensitive situations, it is not uncommon for a human to be more trusted than a computer. As such, these detection missions are reliant on real-time information provided to the human operator, with minimal processing delay.

2) System Requirements: In order for the user to see the heat signatures, the thermal imagery must be down-linked to the user in real-time or near real-time to be useful. It is also desirable for the ground operator to have manual control over the positioning of the camera to improve the view point.

TABLE II

TIR UAS APPLICATION PUBLICATIONS, SORTED BY MISSION TYPE AND YEAR OF PUBLICATION

Ref	Year	Type	Mission
[4]	2003	Detection	Demonstrate Effectiveness of a UAS in fire-fighting operations
[5]	2011	Detection	Used a TIR camera for counting roe deer fawn with a UAS
[6]	2004	Identification	Proposed using a TIR camera to detect frost forming on crops overnight
[7]	2007	Identification	Added thermal imagery to human identification and tracking algorithms for UASs
[8]	2008	Identification	Implemented automated human detection for search and rescue operations with a UAS
[9]	2010	Identification	Implementation of a TIR camera for environmental monitoring applications
[10]	2011	Identification	Advances in mapping thermal imagery for fire fighting decision support operations
[11]	2011	Identification	Development of a hyperspectral mapping UAS that include TIR imagery
[12]	2011	Identification	Automated real-time people and vehicle detection with thermal imagery
[13]	2012	Identification	Used thermal imagery to calculate surface water temperature of streams
[14]	2013	Identification	Identification of subsurface hotspots in a coal mine
[15]	2013	Identification	Thermal mapping of coal fires
[16]	2006	Analysis	Correlated thermal imagery from a UAS with crop health in cotton
[17]	2007	Analysis	Utilized thermal imagery for measuring soil water content
[18]	2007	Analysis	Correlated thermal imagery with crop water stress
[19]	2009	Analysis	Used thermal imagery from a UAS to calculate Crop Water Stress Index (CWSI)
[20]	2009	Analysis	Compared UAS calculated CWSI with other vegetation indices
[21]	2012	Analysis	Correlated thermal imagery with crop water stress
[22]	2012	Analysis	Applied UAS calculated CWSI to peach trees
[23]	2012	Analysis	Applied UAS calculated CWSI to almond groves
[24]	2012	Analysis	Compared UAS calculated CWSI with other vegetation metrics from UAS imagery
[25]	2013	Analysis	Applied UAS calculated CWSI to five fruit tree species
[26]	2013	Analysis	Used thermal indicators to detect faults in drip irrigation systems
[27]	2013	Analysis	Used UAS thermal imagery for the early detection of invasive fungas in olive crops
[28]	2013	Analysis	Compared and correlated UAS thermal imagery with other vegetation indices

The lack of system automation places a limit on the maximum usable information that a thermal imager can provide. Whereas an automated system can differentiate between minuscule differences in temperature, a human cannot. Advanced precision thermal imagers are of little use in detection missions and a lower cost camera or a camera with a faster framerate would be better suited if conditions allow (i.e. daytime with good visibility).

3) Applications: While the previously mentioned law enforcement, search and rescue, and fire fighting applications are the more common applications for thermal imagers on UASs, there are several other applications that fit into the detection mission category. Environmentalists and conservationists have regularly utilized UASs for their efforts, with the UASs providing a cost efficient method for counting or monitoring wildlife [5]. On the other hand, UASs equipped with thermal imagers have also been utilized harmfully, for instance to hunt down wildlife [29]. Thermographic inspection of buildings have also utilized UASs for aerial vantage points, enabling users to spot or detect anomalies in temperatures [30].

B. Identification

UAS applications centered around identification missions require further processing than those centered around a detection mission. Whereas detection missions look to see if something is there, identification missions seek to classify information.

1) Key Attributes: Unlike detection missions, the absolute temperature recovered from a thermal imager is frequently utilized in automated classification systems. Real-time processing can still be an important aspect of an identification system, but total information often takes precedence over real-time. In addition to precise temperature information, identification missions often fuse multiple information sources, such as localization information or other spectral imagery to aid in identification.

2) System Requirements: An identification system requires additional information to be passed down to the ground either in real-time or off-line. While many thermal imagers can easily pass a thermal image, significantly less make the temperature estimates readily available for processing. Additionally, georectification of the video for spatial analysis requires additional information, such as GPS position and aircraft attitude (roll, pitch, yaw), to be passed into the processing stream.

3) Applications: Applications that utilize spatial information and other spectrum information are abundant, though there remains significantly more applications. In one application, a UAS with a thermal imager was used to identify subsurface hotspots in open cut coal mines [14]. In [14], a thermal infrared camera was used to create a high resolution temperature map that enabled the identification of several subsurface hotspots that otherwise would not have been visible. In both of these applications, the precise temperature information and the precise location are utilized to reach the desired end goals.

Automated tracking systems such as the ones found in [7], [12] and [8] utilize thermal imagery in combination with the visual light spectrum to enhance human and car identification and tracking systems for UASs. Other applications include the thermal mapping of rivers [13] and for agricultural applications including the identification of frost damage during cold nights [6]. Another application where small UAS are not currently utilized but would benefit is cave detection and identification [31].

C. Analysis

Analysis missions for UASs with thermal infrared imaging systems require an additional level of processing. Moving beyond simple detection and identification, the goal of analysis missions are to provide actionable intelligence for action based on sound science. The majority of the agricultural and environmental applications of UASs fall under this large category.

1) Key Attributes: The key attribute of an analysis mission is a reliance on calibrated, geo-rectified and multi-spectral imagery. It is this information that actionable intelligence can be calculated from for the end user or further automated control system. Whereas the identification mission answers *where* a hot spot is, the goal of an analysis mission is to explain *why* that area is hotter than the surrounding area and *what* it means to the surrounding area.

2) System Requirements: The system requirements for an analysis mission are similar to an identification mission, but typically there is less of a demand for real-time information over accurate data collection. An analysis mission is often a fusion of several flights of identification missions to track trends or research the dynamics of a region of interest.

3) Applications: While agricultural applications are expected to play a major role for civilian UASs, the literature is sparse with actual implementations with the exception of those that utilize thermal infrared imagery. The biggest goal of agricultural applications for UASs is to find ways to identify crop stress and health before the crops are significantly damaged. While the use of just the visible and near-infrared light spectrum has not been effective, it was noted that thermal imagery shows a correlation between the minor changes in water stress that NDVI imagery cannot [21]. In [19], it is noted that a thermal index known as Crop Water Stress Index (CWSI) can be calculated from thermal imagery gathered by a UAS. While CWSI has been established as an accurate indicator of crop water stress, it has not been widely adopted because it requires a significant number of temperature measurements. Satellite imagery has been regarded as having too coarse of a resolution to provide useful, actionable, information for CWSI. Fortunately, with the advancement of UASs carrying thermal imagers, use of CWSI can be regarded as practical [19]. In [20], further developments of a helicopter-UAS demonstrated that other vegetation metrics such as leaf area index, chlorophyll content (C_{ab}) and water stress could be calculated and validated with the use of thermal imagery. Similar results were found with cotton crops [18], peach trees [22] and almond trees [23]. Initial work on the identification and definition of water stress thresholds for improved management was published in [25].

IV. CHALLENGES

Thermal imagers for UASs are not always as straightfoward as the implementation of other camera systems. In the following section, several aspects of thermal imager integration is discussed including challenges of calibration and mission integration.

A. Calibration

Proper calibration of thermal imagers is necessary to extract scientifically relevant data. This can be a complex process depending on the application. The reader is encouraged to consult relevant literature on general thermal imager calibration processes and recovering thermal data from remote sensing such as [2] and [32]. In this section, a review of the special considerations for the calibration of thermal imagers used in a UAS is presented.

Within a camera system, in addition to the typical lens distortion, the camera must be calibrated to the correct responses. Black body calibration, as described by [9] is a typical method to establish the relationship between the estimated temperature and the measured radiation response on the sensor. In practice, the relationship between the sensor response and the estimated temperature is more complex.

The measured radiance response is a function of surface emissivity (ϵ_λ), transmission of the atmosphere (τ_λ), downwelling ($L^{\downarrow}_{atm,\lambda}$) and upwelling ($L^{\uparrow}_{atm,\lambda}$) thermal radiation. These parameters are driven by factors such as humidity, temperature and the distance to the object. For a TIR UAS application, all of these must be accounted for. There exists models such as MODTRAN5 [33] to account for atmospheric transmittance and upwelling. Downwelling radiation can be measured with a thermal sensor. The emissivity of vegetation is commonly assumed to be fixed and known [34]. Other atmospheric parameters such as humidity and air temperature can be measured in the field during operation. The distance of the object to the lens can be approximated from the flight altitude, although in [20], the distance to an object was also modeled based on the pixel location and the field of view of the camera (e.g. the objects at the edges of the image are farther away than the objects in the center of the view).

The majority of thermal imagers used in UAS applications are uncooled since they are lighter and consume less power [9]. However these systems require extra care due to the effect of external temperature on the accuracy of the thermal imager. In [20], the researchers developed a temperature stabilization period, letting the imager remain on for one hour prior to usage to wait for the imager response to stabilize. In [13], even with a stabilization period and thermal insulation, it was noted that wind blowing over the lens introduced further errors due to convection.

B. Mission Implementation and Strategies

Once software algorithms are developed and camera calibrations are completed, the mission itself should be thoroughly considered. At the core of all data acquisition by means of UAV is the mission itself, which entails intensive mission strategizing and many preflight checks. It is important to remember that price of the equipment being flown, although fairly low-cost in comparison to commercially available solutions and manned aircraft flight, can add up quickly due to crashes as a result of flights without proper planning. In this section, mission logistics, payload choice and integration, and other's strategies are briefly discussed.

1) Mission Logistics: For the purposes of this paper, the relatively broad view of mission logistics will be narrowed to those parameters that directly affect the flight and payload related to TIR data collecting missions. As pointed out in [15], it is crucial that the camera payload is light enough to be flown by a small UAV. The success of the mission is almost entirely dependent on these weight restrictions, which additionally influences the efficiency and performance of the aircraft. Table I has been developed to aid in the selection process of TIR cameras, which includes the approximate weight of each camera payload (excluding extra processing components). Though there are many considerations that will affect TIR missions, the key factors for data acquisition are time-sensitivity of data, weather and time of day, location and camera orientation, and flight path.

Time-sensitivity plays a major role in how the data is collected and processed. For a majority of research-centric flights, imagery data stored onboard the UAV is sufficient and preferred over real-time data feed [9]. These missions are classified as identification missions, which have relatively low urgency and are related to crop monitoring, invasive plant monitoring or hot spot detection, as described in Section III.B. Identification missions have the luxury of storing collected imagery data on local storage drives, allowing for computationally intensive post-processing to occur offline, rather than in real-time. However, there are times when it is not possible to store locally [9] or it is necessary to use a data link, such as in search & rescue or tracking forest fires where time is of the essence [10]. Time sensitive missions, or detection missions as described in Section III.A, require real-time or near real-time imagery that is down-linked to a ground control station. These missions typically stream real-time or near real-time imagery via a modem and data link, which increases power consumption and the overall weight of the payload [9].

For most vegetation monitoring models, when using TIR imagery it is critical to know the ground surface temperature and weather conditions at each data point collected by the UAV [20, 23, 24]. These weather conditions are not limited to: air temperature, relative humidity and barometric pressure. Equally important is the time of day, which effects the TIR imaging directly through the change in the suns orientation throughout the day which can be seen in [24].

The exact GPS coordinate, camera attitude and camera altitude must accompany each image taken. These components are critical in order to properly orthorectify the data collected [24].

Some level of flight path optimization needs to be examined to maximize flight efficiency and minimize the number of flights necessary to cover the area of interest (AOI). The flight plan can be optimized through some methods seen in [3], where resolution is a function of altitude and can be easily manipulated to achieve image footprint area. These calculations during path planning can then aid in determining the amount of coverage desired on a given mission.

2) Payload Choice and Integration: Successful payload integration should account for all conditions in which the UAV will be flying. Creating a robust and light-weight payload is of the greatest importance [15], and accounting for conditions in which small aircrafts are susceptible. These conditions include vibrations, harsh temperatures changes and dust/dirt [15]. Additionally, payload integration dramatically changes between cooled and uncooled TIR imagers where different ventilation strategies are a key factor in image quality. In most scenarios, an uncooled microbolometer will be a desired choice for the weight benefits; however, where weight reduction is favorable, resolution is sacrificed in contrast to cooled imagers. In many cases, it will also be necessary to do some level of TIR data processing directly on the UAV, in which a small embedded computer is the optimal choice. A good example of payload layout can be seen in [9].

Additional measures must be taken to protect the payload, in the unfortunate (and hopefully unlikely) occurrence that the aircraft will not perform as expected and land unsuccessfully. A robust, yet light-weight, enclosure should be designed and implemented to account for this scenario.

When choosing a TIR camera, one can refer back to the applications referenced in Section 2. The TIR camera should be selected based upon mission necessity, paying close attention to spectrum range, resolution, weight and price. Reference Table I for some key specifications provided by the manufacturers of TIR cameras used in research applications.

For larger UAS, a similar survey of six infrared imagers (for military surveillance) was conducted and can be found here [35], where the aircrafts are approximately 200 kg and sensors upwards of 15 kg.

V. CONCLUSION

Thermal infrared cameras can provide significant information that would otherwise be invisible to visible light and near-infrared imagery. In complex and difficult applications such as those in precision agriculture or environmental applications, this provides the necessary valuable discerning data. While the current cost of TIR cameras is relatively high, they provide a significant level of information that can be cost effective.

TIR imagers are especially worth the investment if the mission requires the detection of hotspots such as in search and rescue operations, in structural anomaly detection, or when looking to develop precision agriculture based remote sensing applications for UASs. However, for analysis missions, a TIR system is best utilized as part of a sensor suite. By itself, a TIR is only useful for the simplest of detection missions. Considerable care should be taken when considering a TIR system as it may only be part of a solution when it is a significant investment. However, when utilized properly, they can provide the necessary information that enables high value applications.

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