A Minimum Information Framework for capturing FAIR data with small Uncrewed Aircraft Systems

Andrea K. Thomer -- University of Michigan School of Information; athomer@umich.edu
Lindsay Barbieri -- University of Vermont, Rubenstein School of Environment and Natural Resources; barbieri.lindsay@gmail.com
Sarah Swanz -- Vanderbilt University, Heard Libraries
Jane Wyngaard -- University of Cape Town, Department of Electrical Engineering; jane.wyngaard@uct.ac.za

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Andrea K. Thomer[1,*,†], Lindsay Barbieri[2,†], Jane Wyngaard[3,†], and Sarah Swanz[4,]

[1]University of Michigan School of Information, Ann Arbor, MI, 48104, USA
[2]University of Vermont, Rubenstein School of Environment and Natural Resources, Burlington, VT, 05401, USA
[3]University of Cape Town, Department of Electrical Engineering, Cape Town, 7701, South Africa
[4]Vanderbilt University, Heard Libraries, Nashville, TN, 37203, USA
[*]corresponding author(s): Andrea K. Thomer (athomer@umich.edu)
[†]these authors contributed equally to this work

ABSTRACT

Small Uncrewed Aircraft Systems (sUAS) are an increasingly common tool for data collection in many scientific fields. However, there are few standards or best practices guiding the collection, sharing, or publication of data collected with these tools. This makes collaboration, data quality control, and reproducibility challenging. To that end, we have used iterative rounds of research process modeling and user engagement to develop a Minimum Information Framework (MIF) to guide sUAS users in collecting the metadata necessary to ensure that their data is trust-worthy and shareable. This MIF outlines 74 metadata terms in four classes that users should consider collecting for any given study. The MIF provides a foundation which can be used for developing standards and best practices.

Introduction

Small Uncrewed Aircraft Systems (sUAS) — commonly known as *drones* — are an increasingly important tool for data collection in many scientific fields. However, best practices for sUAS data capture and management are still being developed, and require further refinement and adoption[1]. Researchers in fields such as wildlife monitoring[2], vegetation monitoring[3], atmospheric sciences[4], and in the assessment of built environments and energy infrastructure[5] have all called for the development of sUAS data and metadata best practices. Thus, there is a common recognition of the both immediate and long term value of rigorous data stewardship across many of these fields.

Despite broad consensus that data and metadata best practices are needed, there is still much work to be done developing new standards or practices that address the complex data pipeline and products typical of a sUAS project (see Wyngaard et al.[1] for a detailed discussion of this and Figure 1 for a high level view of a typical sUAS research workflow). Furthermore, while practices, standards, ontologies, and tools of relevance and value exist due to prior work and parallel advances; none are either sufficient or directly reusable in addressing the practical needs of all aspects of sUAS data management, nor has any collection of these become a common or standardise approach to addressing all aspects of sUAS workflows and data products. For instance, the Drontology ontology focuses on describing drone hardware specifications, but not on drone processes or data output[6]. There are well established ontologies currently available for describing observational data[7], sensor platforms and procedures[8], and provenance[9]; and numerous scientific domains have developed ontologies to describe common parameters as understood by that discipline (for instance Climate and Forecast (CF) Metadata Conventions[10] or the environment ontology[11]). But there is a lack of formally modeled ontologies for describing particularly sUAS platforms and flight plans and patterns, and no work has been published showing how these existing components might be used together to describe sUAS data. Similar parallel and partial solutions exist when considering the data workflow stages requiring standard data formats, data product levels, qualified algorithms, and recognised processes.

A framework is needed to help guide sUAS data producers and managers in bringing together these different ontologies, and in creating effective sUAS metadata best practices. This framework should articulate the kinds and classes of metadata needed at a high level. To that end, through extensive sUAS user engagement, we have developed **a Minimum Information Framework (MIF) for data captured with sUAS**. A MIF is a high-level information model outlining key metadata elements (organized into classes) needed to support data sharing, management, and publication[12,13], all in a Findable, Accessible, Interoperable, and Reusable (FAIR) manner[14]. The MIF also articulates the relationships between those attributes (and their classes). This framework is intended to be iteratively revised (even after this initial publication), used in ontology and best practice development, and should inform the selection of formal metadata best practices. The terms in the MIF can be mapped to existing standards and ontologies in creating an application profile. The MIF can also be used as a checklist for different organizations and communities to explore the kinds of metadata that might be important in facilitating data reuse. We developed this framework in collaboration with sUAS producers via the authors' on-going and extensive work building community around sUAS-based scientific research[1]. We additionally developed in depth case studies of real-world case studies of sUAS use for scientific research; conducted systems and workflow analysis; and conducted community surveys.

This framework is not intended as a standard in and of itself, but rather, is a first step towards the development of domain- or institution- specific standards and best practices. We do not provide any guidance about specific tooling or other hardware set-ups that might make data more or less FAIR; we simply outline the metadata elements that are potentially important for the provisioning of FAIR data. We describe the implications of our design further in the discussion section.

Results

We identified 74 terms, divided into the following four classes of information that must be collected to make sUAS data FAIR:

1. **Project metadata**: this class captures information about the project itself, including investigator names and affiliations; project plans, goals, and hypotheses; features of interests; and any access or use restrictions.

2. **Individual flight metadata**: this class captures information about a given flight, its plans, and its actual flight path. The elements in this class are divided into three subclasses: *Flight checks & calibrations*, which capture information about safety and quality checks and corrections; *mission plans*, which capture programmed flight paths and sampling plans; and *platform & payload*, which capture technical specifications about the drone itself and it's hardware.

3. **Dataset from flight**: this class contains metadata about the dataset collected on a given flight. This class is split into two subclasses: the *flight log* subclass, which includes metadata about the actual flight itself (not the planned flight, which is captured in the *Individual flights: mission plans* subclass); and the *observational dataset* subclass, which describes the observational data collected by the flight.

4. **Individual data points**: this class includes metadata to contextualize individual data points within a dataset, including unique identifiers for each observation, and geographic coordinates.

Figure 2 illustrates these classes and their relationships. The full MIF is available via Zenodo[15].

Pilot instantiations of the framework

The MIF can be used by data collectors or archives to begin development of best practices or other guidelines for collecting and curating data. We expect that every group will not need to capture every data element. Rather, the MIF outlines important data types that should be considered in any sUAS project. Research teams may wish to rank terms according to their importance for a given study, context, or organization. We demonstrate the use of the MIF to develop localized best practices with a group from the U.S. Long Term Ecological Research network.

The U.S. Long Term Ecological Research (LTER) network consists of 28 sites each of which serves to both capture baseline ecological data over the long term and facilitate active research. We worked with the team of information managers who manage the data captured at these sites, and whom are increasingly being requested to archive and advise on the sUAS data now also being captured. Managers ranked terms in the MIF according to their importance for given use cases within the LTER. The MIF was then used as the basis for development of LTER metadata guidelines for data gathered with sUAS[16]. These best practices include recommendations for sUAS data repositories, design of sUAS data packages, and examples of semantic annotation. This successful pilot validated the MIF as a useful framework for best practices development.

Additionally, the MIF is being used by the Linked Data and Networked Drones (LANDRS) project (led by PIs Wyngaard and Barbieri) to build automated data annotation software tools for use onboard sUAS using linked data principles and tool stacks as its core[17]. LANDRS shares the assumption underlying the MIF – that this framework will evolve and be implemented differently in different domains – and is therefore building these tools to automatically update as an underlying sUAS data framework is updated. Doing so requires an initial ontology be created. A significant proportion of LANDRS work has therefore been to align existing mature ontologies. The MIF has served as one of the core initial references for this work of building an aligned base sUAS ontology from already established ontologies.

Discussion

The MIF can help structure and prioritize metadata collection associated with sUAS data capture. It is intended to be further refined to better suit specific research and data management needs, as demonstrated in the pilot instantiation of the MIF with

LTER[16]. The MIF is not intended to be a standard, but rather, a reference guide and framework for the development of domain specific standards and best practices. While the MIF is based on more than six years of engagement with the scientific sUAS user community, we note that our development is limited by our working primarily with North American researchers, and during a period in which significant changes have been underway regarding sUAS regulations, sUAS adoption, and sUAS user expertise. Nevertheless, we propose that future users of the MIF will find it serves them well, particularly if they consider some of the following when developing their own sUAS data standards:

Using the MIF to evaluate data trustworthiness and fitness for use

The MIF can be used to develop a rubric for showing what metadata is necessary to render a dataset trustworthy or fit-for-use given a particular set of metadata and a particular use case, as demonstrated in the pilot instantiation of the MIF with the LTER. This rubric could be further used to then evaluate datasets for the presence or absence of this necessary metadata, and perhaps to develop a rough "reusability score" for a collection of datasets. This would be similar to prior work using the completeness of metadata as a proxy for metadata quality[18,19], but with the added advantage of rooting this evaluation in community norms and consensus.

The use of existing ontologies and metadata standards in disseminating sUAS data

Different communities may wish to rely on different ontologies or metadata standards for reasons that suit their individual contexts, and we don't want to limit the applicability of the MIF by constraining it to particular standard or serialization at this moment. As noted in the Introduction, though many of the terms in the MIF are present in established ontologies, there are known gaps in the available ontologies[1,20,21]. The MIF can be used to create an application profile of different standards and ontologies; the resulting data can be serialized as linked data or any other format that makes sense for a given community. Thus, the MIF is a useful tool to aid in bringing ontologies together for sUAS data products, and to guide further ontology development.

Working with software-derived metadata

One underlying concern in this project is the accessibility of software-derived or generated metadata. In some sUAS platforms, not all important metadata are recorded and of those terms that are, the metadata can be hard to access or export, which limits the usability of these platforms for scientific research[1]. We encourage sUAS hardware and software developers to consider the MIF in their work, and ensure that the data we've identified as being likely necessary for scientific use, reuse, discovery, and reproducibility is easily accessible in their stacks. Additionally, we encourage these producers to consider whether raw or derived data are stored and exportable by end users, as these are often needed in scientific contexts.

Methods

The MIF was developed through iterative rounds of community engagement and feedback, as well as systematic analysis of sUAS user data practices. Specifically, we held a series of workshops and community engagement events to build community, better understand user needs, and eventually gain feedback on our proposed framework[1]. We also used a *research process modeling* approach[12] to develop three detailed three in-depth case studies of scientific research with sUAS. We blended these approaches because data and metadata standards must be grounded in community consensus, systematic analysis of the data itself, and in the reality of users' day-to-day practices[22].

Phase I: Community building and research process modeling

We held over 29 workshops, conference sessions, and other community engagement events through organizations the Earth Science Information partners (ESIP), Research Data Alliance (RDA), and American Geophysical Union (AGU)[1]. These efforts resulted in a broad understanding of sUAS metadata needs across fields. During the 2017 ESIP sUAS Data Management Workshop, we identified three distinct cases to serve as exemplars for further metadata development. These included: (1) sUAS-based biodiversity monitoring in Colorado, contributed by researchers at USGS. (2) sUAS biomass and agricultural runoff monitoring, contributed by PI Wyngaard.(3) sUAS atmospheric greenhouse gas monitoring at an agricultural site, contributed by PI Barbieri.

We interviewed key stakeholders for each case (n = 5 total for three cases), and then used these interviews to diagram their workflows, data products, and key parameters and metadata to capture at each stage following the research process modeling method. We developed the MIF based on these results

Phase II: MIF refinement through user feedback and collaboration

The MIF was further refined through a survey of experts (n=11) and additional interviews with sUAS users. We asked survey participants to rank each term on a four-point scale: 1 - "Can't use the data without it"; 2 - "Won't use the data without it";

3 - "Can take it or leave it"; or 4 - "Don't need it, don't bother." We simultaneously conducted hour-long, semi-structured interviews with four scientists who use drones in their field work and who use drone data in their research. We walked through the same survey of terms and asked for responses on the same four-point scale, and received richer responses that helped us better understand how users interpreted the proposed terms in their different domains.

We reviewed and revised our proposed MIF to incorporate this feedback. We found that our survey respondents and interview subjects sometimes offered contradictory opinions on the necessity of a particular term, which typically reflected the needs of their respective domains and the different terms deemed necessary for drone flight operations and management and the terms deemed necessary for data reuse. We consequently left many terms in that wouldn't necessarily be needed be all groups, with the idea that each group could create different application profiles from the MIF.

Phase III: Pilot instantiation of the MIF

The MIF was in a Data Best Practices working group with the U.S. LTER data managers as described above. Through a 6-month collaboration, we demonstrated how the MIF might serve their emerging needs, and simultaneously refined our terms based on their feedback. We worked with their team and users to rank each metadata term according to its usefulness in the contexts of: Discovery (enables search in data archives); Fitness for use (enables an end user to assess whether a dataset will suit their research needs); Necessary for reuse (details that would be needed to reuse, reprocess or otherwise interpret the data). For all three contexts, each term was assigned a value on a scale from 1-5 (where 1 = not important, 5 = absolutely necessary). The LTER information managers and their users provided us with expert input on these value assignments. Based on this input we have now included these rankings in our published MIF, while also noting that these rankings may differ by user communities.

Data Records

The full MIF is available via Zenodo: https://zenodo.org/record/4124167. This archive will be updated as new versions of the MIF are released. As of this writing, the archive contains three files:

1. An entity-relationship diagram (PNG) illustrating key data classes and their relationships
2. a CSV listing the attributes and their definitions for each class. This is the main file for the MIF
3. a data dictionary (TXT) defining each column the the main MIF csv

Zenodo pulls from a Github repository that hosts these files. Users are welcome to fork from this repository directly: https://github.com/akthom/sUAS_MIF.

Usage Notes

As noted above, the MIF is meant to serve as a jumping off point for further standard, best practice, or ontology development. It does not provide any specification on tooling or specific standards to use. We ask that users cite this data paper and/or the Zenodo repository if they draw on this work in their research or standards and best practices development work.

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Author contributions statement

A.T., L.B. J.W. conceived of the study. L.B., J.W. provided expert input. A.T., L.B., J.W., S.S. designed surveys and interviews. A.T., S.S. conducted interviews. A.T., L.B., S.S., J.W. analyzed data and refined the MIF. L.B., J.W. implemented and refined MIF. A.T., L.B., J.W., S.S. wrote and reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Figures & Tables

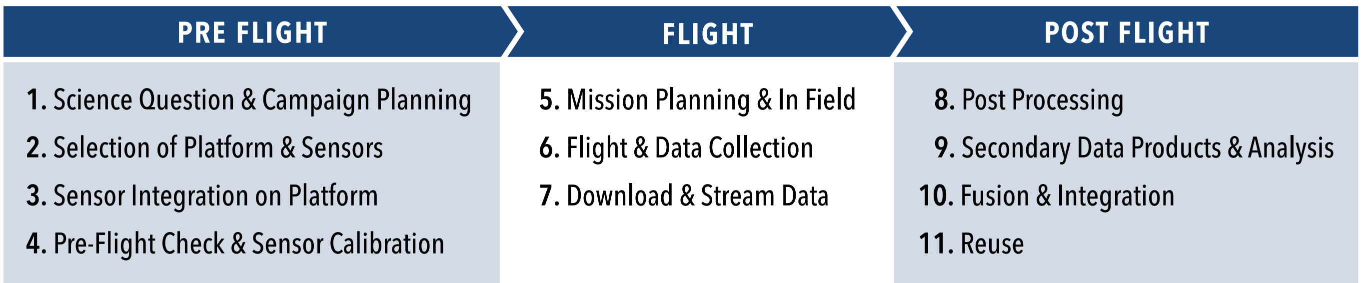

Figure 1. A high-level drone research workflow

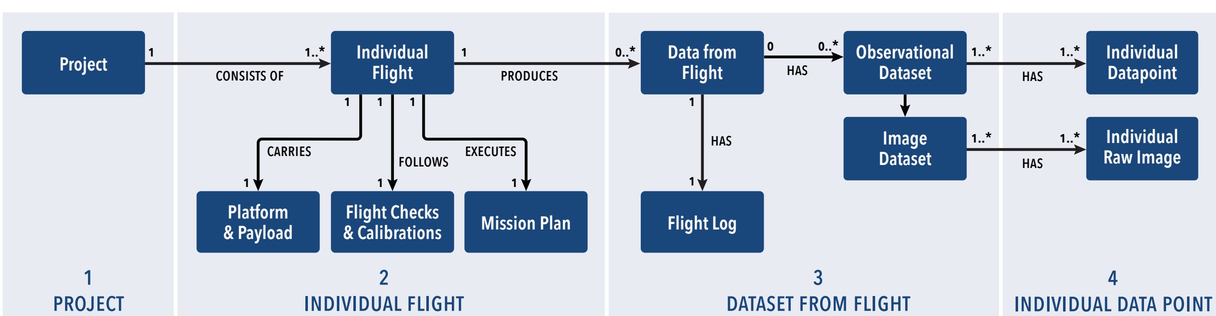

Figure 2. Core Classes of The Minimum Information Framework for sUAS datasets