INTEGRATION OF REMOTE SENSING TECHNOLOGIES WITHIN DECISION SUPPORT SYSTEMS FOR THE ENFORCEMENT OF ILLEGAL DUMPING: PRINCIPLES AND NUMERICAL SIMULATIONS

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ABSTRACT

In recent years, the Italian Aerospace Research Centre has worked in support of public institutions to explore the potential use of remote sensing data for monitoring illegal micro-dumps in the Campania region, Italy. This experience has led to the definition of a ‘progressive monitoring’ approach, capable of using different remote sensing technologies at different stages, including satellite, despite its limitations in spatial resolution compared to the targets to detect and identify. This paper discusses the use of this technology and illustrates how it is possible, during the design phase, by means of simulations, to quantify the expected results based on cost-related satellite monitoring parameters, such as the acquisition and processing period, considering the specific application scenario and the monitoring goals.
Keywords: remote sensing, illegal dumping, environmental monitoring, decision support systems.

1 INTRODUCTION

Illegal waste management is one of the major environmental issues in both industrialised and developing countries. This phenomenon requires continuous monitoring to make public authorities fully aware of the necessary actions for the prosecution of criminal actions and the restoration of the affected sites.

In Italy, the Campania region, with particular reference to the area comprised between the cities of Naples and Caserta, is sadly known as the ‘Land of Fires’ due to the frequent arson of illegal dumping sites [1]. Since 2014, the regional government activated a process of systematic monitoring of the phenomenon through its in-house company SMA Campania. Its activities are executed via on-ground patrolling aiming at the collection of information about the status of illegal dumps, with particular attention to the storage of dangerous materials (e.g., asbestos) and the accumulation of materials potentially subject to arsons. This phenomenon is a consequence of illegal dumping.

The surveys led to the identification of areas particularly affected by the presence of micro-dumps, mainly due to the illegal disposal of waste from industrial (construction, manufacturing) and agricultural activities.

Under the aegis of a previous project, the Italian Aerospace Research Centre (CIRA) contributed to the exploration of the potential use of remote sensing images in discovering areas affected by micro-dumps [2]. This evaluation aimed at the enhancement of the effectiveness of ground patrolling, which is crucial for characterising dump sites and reporting their status to authorities, and to extend the discovery to areas far from the roadside, which are the most monitored by patrols. To this end, the need for a continuously updated picture led to the choice of satellite imagery, in particular very high resolution (VHR) optical data with sub metric resolution, against aerial data that are commonly used by local public administrations for territory management.

Although satellite data have rather critical spatial resolution compared to the size of the micro-dumps, whose extension could be in the order of a few square meters, they offer

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significantly lower acquisition costs, the possibility of high revisit frequency and wide territorial coverage. Therefore, their use can be strategic if contextualised in an effective monitoring process.

For these reasons, CIRA proposed the concept of ‘progressive monitoring’ [3]. The aim is to define various stages of the monitoring process, each one suitable to be implemented with a specific platform (satellite, aerial, close range) to be integrated with on-ground surveys. Such a process has been also supported by the development of demonstrative modular technologies and by a decision support system (DSS) [3] able to integrate all such components and support the process at each stage. In particular, algorithmic developments have been proposed for the detection of micro-dumps in satellite VHR images and to automatically generate unvalidated map products for subsequent validation by photo-interpreters (Fig. 1). In particular, both traditional machine learning [4] and deep learning [5] based techniques have been recently proposed and validated.

Figure 1: Micro-dumps automatically detected in VHR satellite imagery by means of a target detector based on scattering transform [4].

Compared to aerial orthophoto [6], the usage of satellite detection products faces considerable challenges due to the limited spatial resolution and accuracy, resulting in a scarcity of literature on this subject. However recent studies [5] show that satellite detection maps, even if relatively inaccurate (precision and recall of deep learning based detectors are in the order of 75% and 48%, respectively), can be employed as a preliminary discovery tool in order to identify small areas of territory affected by the dumping phenomenon (precision and recall are respectively estimated as 59% and 91% for such type of classification task on hexagonal cells of 110 m apothem).

In this study, we illustrate the development of a framework aiming at the assessment of satellite imagery exploitation in tackling illegal waste disposal. Additionally, we highlight that, despite the current limitations in satellite detection performance, this technology holds the potential to significantly contribute to the effective management of the phenomenon through the exploitation of progressive monitoring concepts. They are illustrated in Section 2, together with the developed DSS. In Section 3, the impact of the diverse parameters feeding the system is explored through numerical simulations. Conclusions are drawn at the end of the work.

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2 INTEGRATION OF REMOTE SENSING DATA WITHIN A DSS

The modelling of the illegal dumping monitoring process relies on quantitative describing its primary components, i.e., the generation and accumulation of illegally abandoned waste and the activities implemented for waste removal and site remediation. To the best of our knowledge, existing literature has not offered any solution to describe these processes. Here, a Markov chain (MC) is proposed.

The modelling of processes with unknown statistics via MCs is a common practice across diverse fields and has previously been employed to describe the waste generation process [7]. However, it has never been specifically implemented for illegal micro-dumps.

The representation shown in Fig. 2 represents a finite state machine with probability associated with state transitions. Reporting activities (signalling) enabling remediation actions have also been included in the model. The states of the system are composed of the vector of components 'E' (existent = 1, not existent = 0) and 'S' (signalled for remediation = 1, not signalled = 0). The transition probabilities of the process are defined by the generation probability P_g and the remediation probability P_r. The probability of micro-dump discovery, P_d, is related to the performance of the monitoring system.

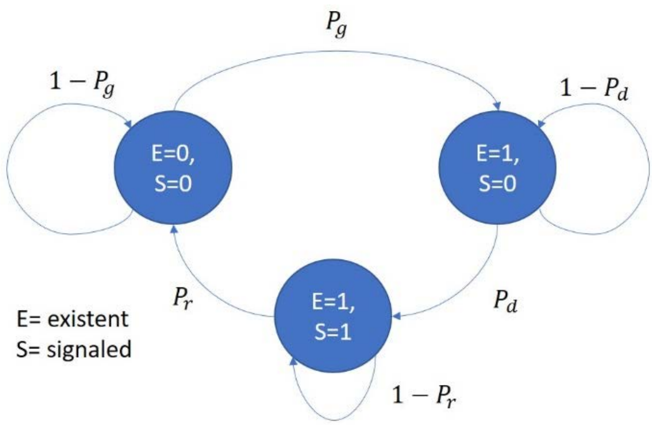

Figure 2: The Markov chain used to represent the enforcement of the illegal dumping process, from generation, to discovery and remediation.

The state transition probability matrix T of the MC is reported in eqn (1). In this model, a location not affected by the micro-dumping can become affected with probability P_g. The site can be discovered (using satellite monitoring or on-ground monitoring) with probability P_d. The remediation action on a discovered site are performed with probability P_r.

$$T = \begin{bmatrix} 1 - P_g & 0 & P_r \\ P_g & 1 - P_d & 0 \\ 0 & P_d & 1 - P_r \end{bmatrix}. \tag{1}$$

In the following, we provide some insights about the envisioned DSS, which is based on satellite monitoring. We compare its performance, in terms of fraction of locations affected by the dumping phenomenon, with traditional on-field monitoring using numerical simulations derived from the previously discussed MC system.

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The concept of progressive monitoring [3] refers to the exploitation of different remote sensing technologies to gather increasingly detailed information. This way, spaceborne imaging systems, with high temporal frequency and broad spatial coverage but low spatial resolution, are complemented by close-range platforms offering higher spatial and/or spectral details. Therefore, the role of the spaceborne imaging system is to aid the selection of a limited number of locations for further investigation using aerial platforms, which typically entail higher operational costs.

Progressive monitoring is organised in three steps. First, the area of interest is periodically imaged with VHR satellite data with a ground sampling distance (GSD) lesser than 50 cm. Ultra-high resolution (UHR) aerial images with GSD lesser than 10 cm are acquired during dedicated campaigns to generate ground truth and/or to validate satellite detection products [6]. Finally, close-range remote sensing is implemented to characterise small micro dumps using drones equipped with custom payloads [7] obtaining 2D or 3D reconstructions of centimetric spatial resolution. Ground surveys are performed, as usual, to confirm and characterise the detected locations and/or to discover new dumping locations.

The data acquired via progressive monitoring feed a DSS, whose general architecture is depicted in Fig. 3: It is composed of five major processing blocks. The data gathering block is devoted to the collection and organisation of progressive monitoring data. They feed the data fusion block. Its objective is the handling of such multisource data and their disambiguation in case they refer to the same location. The output of this block is the provisioning of a detection product constituting the base for further processing within the DSS.

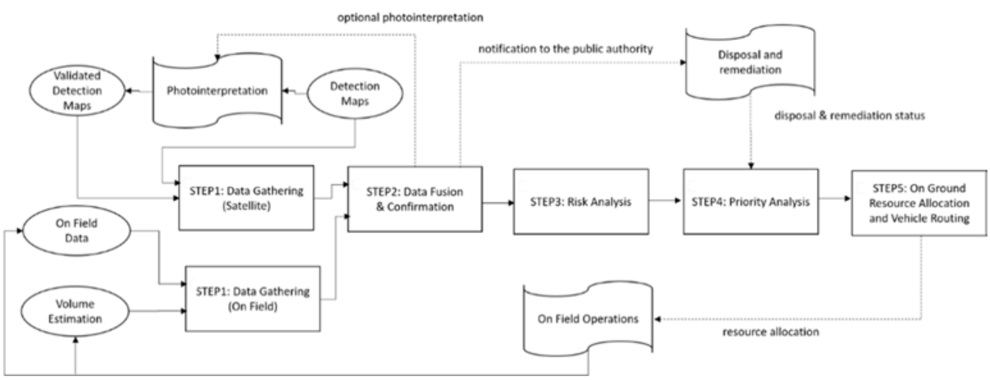

Figure 3: Architecture of the proposed DSS.

The risk analysis block is devoted to the evaluation of the potential environmental impact of each micro-dump on the surrounding area. This assessment relies on various factors, including dump characteristics, such as composition, and volume, alongside external variables, like population density, urban texture and land use [8]. Given the detection system’s limited accuracy, the probability of micro-dump existence can be estimated and weighted in the risk expression, as also previously proposed for the localisation of potential illegal dumping sites [9].

The concept of priority analysis has been introduced also in other works for discovery purposes [10], [11]. Here, binding the concept of priority with the final goal of the application, the remediation, is introduced to quantify the expected risk reduction in the case of on-site inspection and consequent activation of remediation activities. A site associated to a high environmental risk could have low priority inspection if it has already been reported to the competent authorities. The need to re-inspect a site previously surveyed depends on the generation and remediation dynamics, which are introduced into the DSS mainly for this specific need.

The last block of the DSS is devoted to on-ground resources allocation and vehicle routing. In fact, the final objective of the DSS is to assist in deciding which areas require inspection considering available information and resources, intended as number of vehicles and operators needed for patrolling. In other words, the final output of the system is the optimal route, given the problem constraints, indicating the sites to be inspected and their priority [12]. To this aim the region of interest is partitioned in a finite number of inspection cells.

3 NUMERICAL SIMULATIONS

The following numerical simulations aim to show the impact of some parameters of the progressive monitoring system on the performance of the remediation process, also in comparison with a monitoring strategy that does not use remote sensing data.

The numerical simulations reported in this section compare the probability of the dumping phenomenon over the monitored inspection cells two scenarios: one using solely ground surveys (traditional monitoring) and the other employing the progressive monitoring approach. In both the cases, the on-ground exploration strategies are optimised on the underlying generation and remediation processes using a state estimator based on the MC model. The inspection plan is produced after such state estimation phase.

In traditional monitoring, the probability of discovery is basically related to the patrol exploration rate (how many cells can be inspected per day). With remote sensing, such probability depends on the performance of the exploited detection algorithm and on the time frame between the processing of two successive satellite images to produce detection products. This time, as shown in Table 1 reporting the default simulation parameters, has been set to 60 days, i.e., a new image is ingested into the DSS system on a bi-monthly basis. This is due to the relatively slow dynamic of the phenomenon of generation of new dumps, here set to 112 days. The default simulation parameters are synthetically reported in Table 1.

Table 1: Simulation default parameters.

Parameter	**Value**	**Unit of measurement**
Remediation time (RT)	28	Days
Generation time (GT)	112	Days
Patrolling coverage speed (PCS)	10%	Percentage of inspected cells per day
Satellite acquisition period (SAP)	60	Days
Satellite recall (SR)	90%	Percentage
Satellite precision (SP)	80%	Percentage
Initial micro-dump distribution (IDD)	15%	Percentage

The simulation results are reported in Fig. 4: for traditional monitoring (blue curve) and progressive monitoring (red curve). The *y*-axis reports the probability that a micro-dump exists in a monitored location. Assuming that the precision of the satellite detection algorithm is in the order of 80%, it is observed that progressive monitoring provides better performance. They are not constant but show an oscillation which is a function of the parameter satellite acquisition and processing (SAP) period.

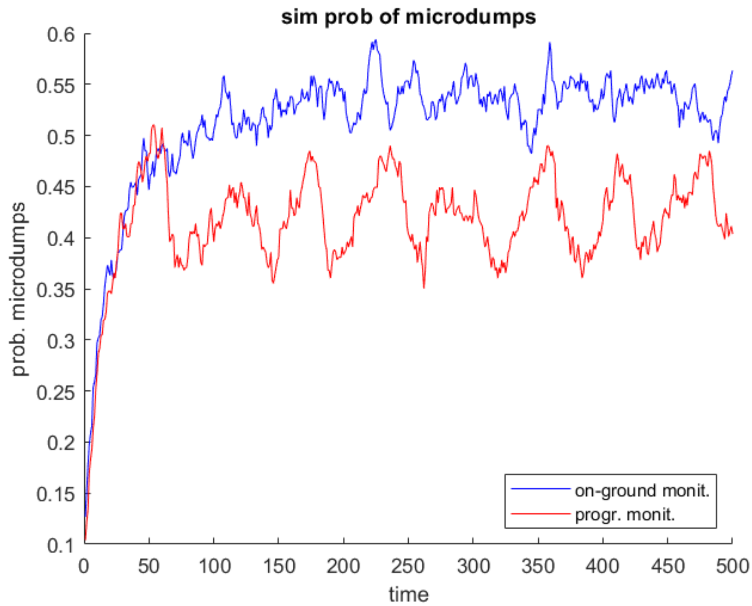

Figure 4: Performance in terms of probability of micro-dumps over the monitored cells (lower is better) of the proposed progressive monitoring approach (red curve) compared to traditional monitoring results (blue curve).

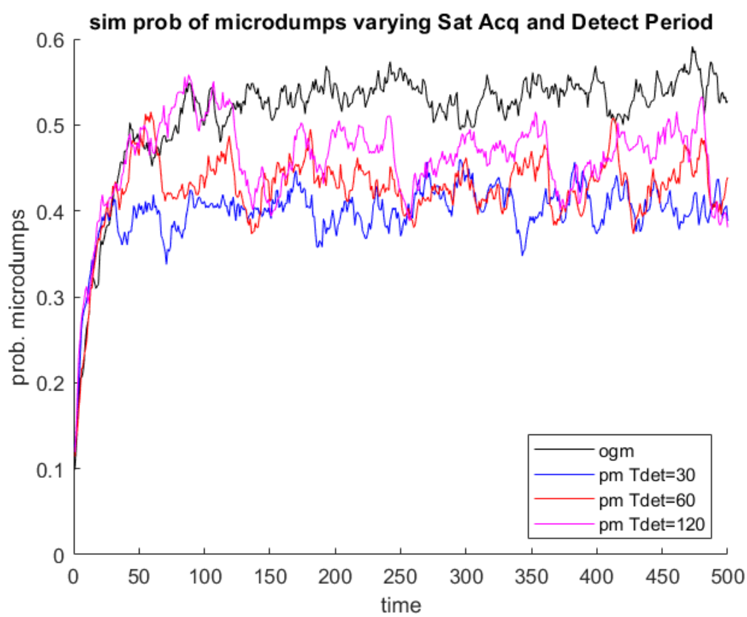

Figure 5: Performance of the proposed progressive monitoring approach for different values of the SAP parameters (30, 60, and 120 days).

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As aforementioned, the parameters of the satellite monitoring system can impact on the performance of the proposed approach. One of them is the SAP parameter, whose effect is evaluated in Fig. 5. As expected, the performance has the same periodic trend whatever the SAP. It improves immediately after the provisioning of a new detection product and decreases as soon all the indicated locations are inspected. As expected, the average performance increases as the SAP parameter decreases.

4 CONCLUSIONS

In this article, we proposed a design methodology for a progressive monitoring process targeting illegal micro-dumps, with a specific focus on the satellite detection system. The expected performance of the system is evaluated based on statistical assumptions concerning the generation and remediation dynamics of micro-dumps and according to some system parameters, like the satellite acquisition and processing period and the performance of the satellite detection algorithm.

The principal novelty here introduced is the development of a framework that, thanks to simulations of the waste generation, discovery and disposal processes, based on MC modelling, allows for the estimation of the performance of the monitoring system, thus providing operators and decision makers with a tool exploitable in the design of DSS's focusing on the tackling of illegal dumping.

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