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An IoT/IoE-Based Integrated Security and Safety System for the Royal Palace and Gardens of Caserta, with a Genetic-Algorithm Method for the Optimal Design of Perimeter Video Surveillance

Alberto Bruni [1,2] and Fabio Garzia [1,2,3,4,*]

1 Safety & Security Project, Royal Palace of Caserta, Ministry of Culture, 81100 Caserta, Italy
2 Security Project & Smart@Pompeii Project, Pompeii Archaeological Park, Ministry of Culture, 80045 Pompeii, Italy
3 Safety & Security Engineering Group—DICMA, SAPIENZA—University of Rome, 00184 Rome, Italy
4 Wessex Institute of Technology, Ashurst Lodge, Ashurst, Southampton SO40 7AA, UK
* Correspondence: fabio.garzia@uniroma1.it

Abstract

Monumental heritage sites must be protected as rigorously as critical infrastructures, but under aesthetic and architectural constraints that limit where protection technologies can be installed; the purpose of this study is to reconcile effective security with minimal impact on the historical fabric. The paper presents the integrated security and safety system realized for the Royal Palace and Gardens of Caserta, a UNESCO World Heritage Site visited by around one million people per year. This system includes an Internet of Things/Internet of Everything framework integrating a 3D supervision platform, a resilient park-wide network, video surveillance, emergency communications, an artificial-intelligence engine and visitor services. Perimeter video-surveillance design is formulated as a constrained multi-objective optimization problem (coverage, camera count, overlap, reuse of existing installation points) solved with a purpose-built genetic algorithm and characterized through 311 optimization runs and 216 baseline runs on synthetic perimeter instances. The algorithm reached 95–98% perimeter coverage while reusing 95–100% of existing installation points, converging within 120–410 generations. Two greedy baselines were respectively quantified: the price of the aesthetic objectives (a 29–41% camera overhead with respect to a coverage-only design) and the specific contribution of the joint optimization (an order-of-magnitude reduction in coverage redundancy at equal reuse of existing installation points). Sensitivity analysis exposed the coverage–cost trade-off. The framework and method provide a reproducible, quantitatively characterized approach to minimally invasive heritage security design that is transferable to comparable sites.

Keywords: cultural heritage security; security management; safety management; internet of things; internet of everything; video surveillance; camera placement; genetic algorithms; multi-objective optimization; UNESCO World Heritage

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1. Introduction

The protection of monumental heritage sites is a problem of critical-infrastructure engineering with an additional non-negotiable constraint: the site itself (its walls, its vistas, its fabric) must not be altered by the very systems that protect it. Cameras, cabling, network nodes and loudspeakers that would be routine in an airport or an industrial plant must here be placed under aesthetic and architectural restrictions, often on listed structures where new fixings are limited or forbidden. At the same time, the protection goals are broader than in most infrastructures: alongside the security of people and the safety of crowds, the heritage asset itself must be preserved and its accessibility guaranteed, with particular attention to visitors with disabilities and to the personnel who operate the site.

The Royal Palace of Caserta (RPC) concentrates all these difficulties in a single site. Commissioned by Charles of Bourbon, who in 1734–1735 had conquered the kingdoms of Naples and Sicily and intended to endow his kingdom with a new capital away from the sea and its threats, the palace was designed in 1752 by Luigi Vanvitelli and completed by his son Carlo Vanvitelli and other architects of the same school. The main building occupies about 45,000 m^2 over five floors, with four monumental courtyards, 1200 rooms, 34 stairways and 1742 windows, reaching a height of 36 m; its interiors (the grand marble staircase, the royal apartments, the Palatine Theatre, the Picture Gallery and the library) are among the most celebrated of European Baroque architecture. The palace faces a park that extends for 3 km over about 120 hectares, comprising the geometric Italian garden, with its progression of pools, waterfalls and fountains culminating in the Great Cascade, and the naturalistic English garden. Together with the Vanvitelli Aqueduct and the San Leucio complex, the palace and park were inscribed in the UNESCO World Heritage List in 1997 [1]. The site hosts concerts, exhibitions and film productions and is visited by around one million people per year, with a steadily increasing trend interrupted only by the pandemic period. A view of the palace is shown in Figure 1 and of its interiors in Figure 2.

Figure 1. Royal Palace of Caserta, view from the Royal Garden. Photograph by M. Del Torchio, Wikimedia Commons, CC0 1.0 [2].

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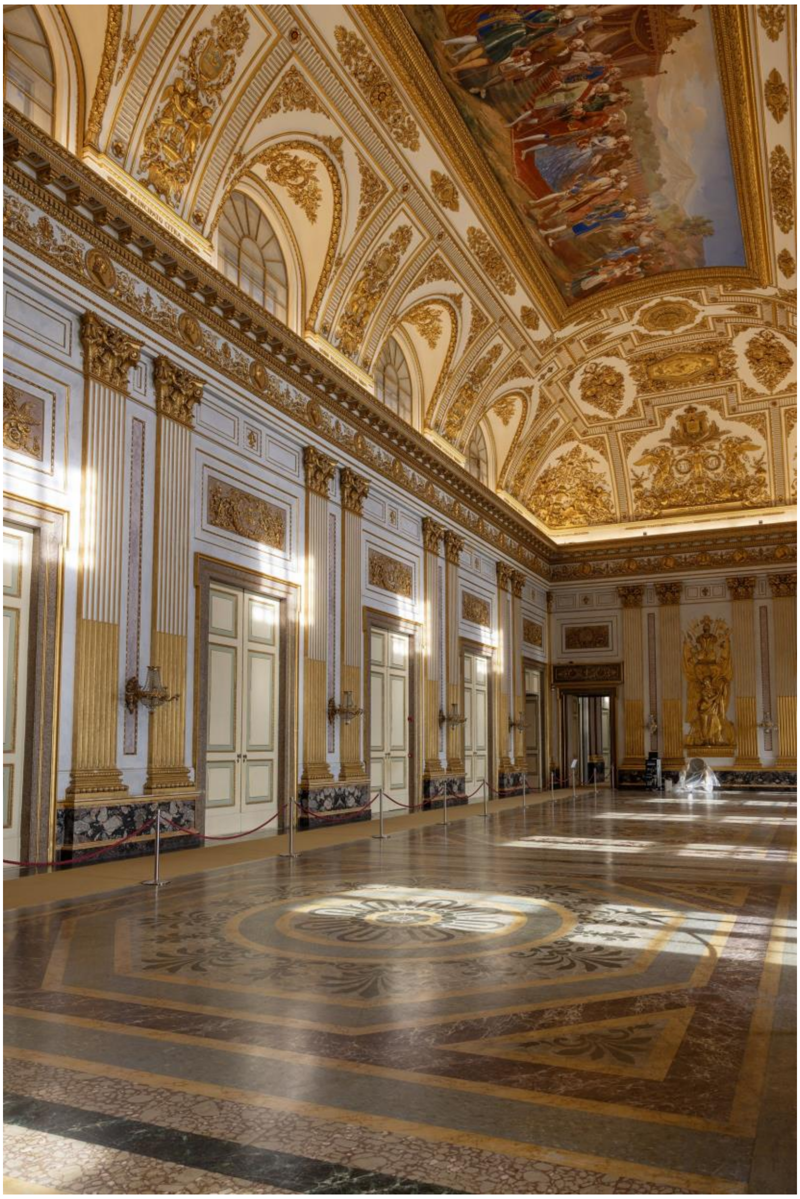

Figure 2. Royal Palace of Caserta, Throne Room. Photograph by M. Del Torchio, Wikimedia Commons, CC0 1.0 [3].

The scale and character of the site shape the security and safety problem in specific ways. The visitor experience is emotionally intense (a study of visitors' reactions based on the semantic analysis of social media content found "attraction" to be the dominant emotion, accounting for about 45% of emotionally connoted terms (anyway, the total percentage of positive emotions is about 96%), with negative emotions nearly absent [4]), and this emotional engagement coexists with objective risk factors: large daily crowds concentrated along obligatory routes, a 3 km garden axis distant from immediate assistance, extensive perimeter walls, and the constant tension between openness to the public and the protection of irreplaceable assets. Managing this complex requires more than the juxtaposition of conventional subsystems. It requires an integrated, multidisciplinary management model and a technological framework able to implement it without violating the constraints of the historical fabric, a need increasingly recognized in the literature on smart technologies for heritage preservation [5,6].

This paper makes two contributions. First, it presents the complete IoT/IoE-based integrated security and safety system designed and realized for the RPC within the site's

Safety and Security project, started in 2019: the supervision platform, the control room and data centre, the communication network, the video surveillance, public-address and radio subsystems, the artificial-intelligence engine and the visitor-facing services (Sections 4 and 5). The system continues a line of integrated designs developed by the authors' group for complex Italian sites (the Vatican City State [7], the Senate of the Italian Republic [8], the Fellini Museum of Rimini [9] and the Pompeii Archaeological Park [10]) and adapts it to the specific profile of a Baroque royal residence with a monumental park. Second, it formalizes and characterizes the method used to design the perimeter video-surveillance system: a genetic algorithm (GA) that simultaneously optimizes the number, position and optical configuration of the cameras under coverage, overlap and aesthetic-impact objectives (Section 6). With respect to the group's previous applications of evolutionary design [9,11], the present work contributes the complete formal specification of the encoding and fitness function, a set of methodological refinements that make the algorithm reproducible, and, most importantly, a systematic simulation campaign of 311 optimization runs and 216 baseline runs with confidence intervals, convergence analysis, weight-sensitivity analysis and a comparison against a coverage-only and a bracket-aware greedy baseline (Section 7). The characterization reported in Section 7 is conducted on synthetic perimeter instances. The corresponding parameters of the realized RPC installation—the geometry of the admissible installation points, the final camera layout and the residual coverage gaps—are not disclosed in this paper: for an operating high-value heritage site they are themselves security-sensitive information, and publishing them would work against the purpose of the system described here.

The design problem addressed by the second contribution can be stated in words already at this point and is formalized in Section 6.1. A perimeter wall of known length must be watched by fixed cameras that can be installed only on a discrete set of admissible points: the brackets that already exist on the wall and the positions where a new fixing is admissible under the conservation constraints of the site. Each camera watches a stretch of wall whose length is set by its optics and is interrupted at the first bend. The designer must choose how many cameras to install, where, and with which optics, so as to cover the perimeter with as few cameras and as little redundancy as possible while using the brackets that already exist and adding as few new fixings as possible to the historical fabric. The last two requirements are what separates the heritage version of the problem from its standard formulation: they are objectives to be optimized, not constraints to be satisfied.

Three questions organize the study. First, can a single IoT/IoE framework carry security, safety and visitor services on a monumental site without violating the constraints of its historical fabric? Second, can the resulting camera-placement problem, with the reuse of existing installation points as an explicit objective, be solved by a genetic algorithm whose behaviour is stable and predictable across problem sizes and site conditions? Third, what is the quantitative price of the heritage objectives, measured against designs that ignore them? Sections 4 and 5 answer the first question, Sections 6 and 7.2–7.4 the second, and Section 7.5 the third.

The remainder of the paper is organized as follows. Section 2 reviews related work. Section 3 summarizes the site profile and the resulting requirements, and The Interface Between Conservation and Technological Design describes the interface between the conservation competence and the technological design. Section 4 presents the management model and the technological framework. Section 5 describes the realized subsystems. Section 6 formalizes the camera-placement problem and the genetic algorithm. Section 7 reports the simulation campaign. Section 8 discusses findings and limitations, and Section 9 concludes. In terms of the structure recommended by the journal, Sections 3–6 together constitute the Materials and Methods of the study—the site and its requirements, the management model and the technological framework, the realized system, and the design method—while Section 7 reports the Results, Section 8 the Discussion, and Section 9 the Conclusions.

2. Related Work

The IoT and its heritage applications. The technological substrate of the present work is the Internet of Things, whose architectural foundations were laid in the classical surveys of Atzori et al. [12] and Gubbi et al. [13]: pervasive sensing, standardized connectivity and cloud-side intelligence composed into application-domain platforms. Cultural heritage was an early adopter on the valorisation side (smart-museum architectures connecting exhibits, sensors and visitors were prototyped in the mid-2010s [14], and indoor location-aware museum services demonstrated the visitor-facing potential of the paradigm [15]) and has more recently embraced it on the conservation side, where energy-efficient IoT architectures for the preventive conservation of cultural property [16], wireless sensor platforms deployed at museum scale to monitor and model the indoor environment [17] and open-source hardware sensor networks installed in monumental buildings [18] have made continuous environmental surveillance affordable over large surfaces, while wireless sensor networks for the continuous structural health monitoring of historic masonry towers [19] extend the same instrumentation to the structural response of the fabric. The convergence of IoT sensing and artificial intelligence in heritage preservation has grown into a substantial literature, recently synthesized by Laohaviraphap and Waroonkun [6], whose systematic review of 92 studies documents the shift from reactive conservation to continuous monitoring and predictive analytics. The same trajectory feeds the digital-representation thread (from historic building information modelling [20] and its diagnosis-oriented extensions [21], reviewed for heritage science in [22], to digital twins for preventive conservation [23], whose state of the art has been mapped in this journal [24]), which shares with the present work the ambition of a single, continuously updated informational counterpart of the physical site.

Heritage security, safety and risk management. The protection of heritage assets against intentional and accidental threats has its own consolidated tradition: systematic risk-management methodology for cultural property [25], the engineering discipline of physical protection systems [26], the professional practice of museum security [27], and quantitative vulnerability indices developed to prioritize preventive conservation on monumental assets [28]; the hazard side of the same equation is being reshaped by climate change, of which the impacts on cultural heritage have been reviewed systematically [29]. Fire deserves a separate mention, both for the value at stake and for the difficulty of retrofitting historic fabric: domain-specific fire-risk assessment for historic buildings [30], the methodological principles of fire safety engineering applied to heritage [31] and the analysis of recent catastrophic losses [32] converge on early detection and continuous supervision as the measures most compatible with conservation constraints. Visitor safety adds a further dimension, increasingly treated quantitatively: the measurement, modelling and optimization of visitor flows in crowded museums [33], supported by the wider body of crowd-motion simulation models [34], and personalization-oriented smart-tourism services [35] resting on the smart-tourism foundations codified in [36] both rely on the same sensing infrastructures that security requires. What remains comparatively rare in this literature is the integration of security, safety and visitor services into one technological fabric, and this is the specific tradition to which the present work belongs: the integrated security systems of the Vatican City State [7] and of the Senate of the Italian Republic [8] established the model of a single multi-service network for institutional sites; the Fellini Museum of Rimini [9] introduced evolutionary optimization in the design of the integrated system network of a museum; and the Pompeii Archaeological Park system [10] demonstrated the full IoT/IoE paradigm (connecting people, things, data and processes) at the scale of a 66-hectare archaeological site, supported by a multidisciplinary management model formalized in [5] and by a purpose-designed communication network [11].

Camera placement as an optimization problem. The theoretical root of the video-surveillance design problem is the art-gallery problem: Chvátal's theorem establishes that $\lfloor n/3 \rfloor$ guards suffice for a polygon of n vertices [37], and the associated algorithmic theory is collected in O'Rourke's classical monograph [38], whose randomized descendants first brought the abstraction close to deployable sensor networks [39]; the practical problem with real sensors (finite field of view, finite range, occlusions, cost) is NP-hard, being reducible to set covering. Practical formulations therefore rely on approximate or metaheuristic methods: Erdem and Sclaroff's formulation of camera layout under task-specific coverage requirements [40] is the standard engineering reference, complemented by set-cover-based placement of multiple visual sensors [41], optimal camera-network configuration for task-specific visual coverage [42], general sensor-planning methods accounting for occlusion [43] and spatial-optimization formulations addressed explicitly to security monitoring [44]; the alternatives to the evolutionary approach, from particle-swarm-inspired probability algorithms [45] to dynamic-programming coverage optimization [46], are surveyed together with the rest of the field in the comprehensive review of camera planning for large-area surveillance [47]. The design problem is today inseparable from the processing side, since modern surveillance value lies increasingly in the analytics layer [48], where deep-learning anomaly detection has become the dominant paradigm [49]. On the optimization-machinery side, genetic algorithms (rooted in Holland's foundational work [50], systematized by Goldberg [51] and made accessible to engineering practice by Whitley's tutorial [52]) remain natural candidates for mixed discrete problems in which the decision variables (installation point, lens focal length, sensor format, activation) are heterogeneous and the objectives conflict; their modern landscape is surveyed in [53], and their multi-objective descendants such as NSGA-II [54] define the natural evolution path of the method presented here. The formulation of this paper differs from generic camera-placement work in one respect that is essential in heritage contexts: the reuse of existing installation points and the minimization of new fixings on historical walls enter the objective function explicitly, so that aesthetic impact is optimized rather than merely constrained.

With respect to this literature, the contribution of the present paper is the combination of the threads above: a site-scale IoT/IoE integrated system in the heritage security tradition [7–11,35] and a fully specified, statistically characterized GA for perimeter camera placement in which heritage constraints are first-class objectives.

3. Materials and Methods: The Site and Its Security and Safety Requirements

Table 1 summarizes the dimensional profile of the site and the main protection-relevant characteristics.

Three requirements follow directly. First is integration: the heterogeneity of the risks (intrusion, crowd safety, environmental, hydrogeological, seismic) and of the assets requires a single supervision layer rather than parallel vertical systems. Second is resilience: the extension of the park and the presence of events require subsystems that keep operating under partial failures of power or connectivity. Third is minimal invasiveness: every field installation (camera, antenna, loudspeaker, network node) must respect the constraint that the monument is not available as an ordinary support; existing brackets, poles and cavities must be reused wherever possible and new fixings minimized. The last requirement is not a soft preference: it shapes the design problem of Section 6, where it becomes an explicit term of the objective function.

Table 1. Profile of the Royal Palace and Gardens of Caserta and related protection requirements.

Element	Value/Character	Protection Implication
Main building	~45,000 m^2, 5 floors, 1200 rooms, 4 courtyards, 36 m height	Interior surveillance, access control, wayfinding, asset protection
Windows/stairways	1742/34	Extended intrusion surface; complex evacuation paths
Park	~120 ha, 3 km main axis, Italian + English gardens	Long perimeter; areas remote from assistance; limited installation points
Water features	Pools, waterfalls, fountains, Great Cascade	Drowning risk; environmental monitoring
Visitors	~1 million/year, strongly seasonal, large events	Crowd management; emergency communication; accessibility
Status	UNESCO WHS (1997), listed structures throughout [1]	Aesthetic constraints on any installation; reversibility

The Interface Between Conservation and Technological Design

The requirement of minimal invasiveness is not met by a technological choice: it is met by a division of labour between two professional domains, and it is worth making that division explicit because it determines what the technological design is allowed to do. On one side stands the conservation and restoration competence responsible for the historical fabric: the assessment of which surfaces may receive a fixing and which may not, the reversibility of every intervention, the protection of the designed views and of the historical landscape, the compatibility of materials and finishes, and the authorizations of the competent heritage authority. On the other stands the engineering competence responsible for protection performance: sensing coverage, network resilience, emergency communication and service continuity. Neither domain can decide alone where a camera goes.

The two domains meet in a single artefact: the survey of admissible installation points. It is the conservation side that decides which positions belong to the set EBs already present on the wall and which further positions may be admitted to the set of NBs; it is the engineering side that decides how to use them. That survey is therefore the operational form of the dialogue: everything the conservation competence has to say about invasiveness is expressed in it, and nothing outside it constrains the design. Three properties make the interface work in practice. First, it is expressed as a set of positions rather than as a prohibition in prose, so that it can be handed over unambiguously and, as Section 6 shows, consumed directly by a design algorithm. Second, it is revisable: a position excluded at first may be readmitted if a reversible fixing or a different mounting is agreed upon, and the design can then be recomputed at no cost, which turns a negotiation that would otherwise be adversarial into an iteration. Third, its quality is measurable in the outcome: Section 7.2 shows that the availability of admissible positions, and not the optimizer, is what bounds the coverage a site can achieve, so the effort invested in the survey is itself a quantifiable contribution to the protection of the site.

The same interface governs the other field elements of Section 5—network nodes, access points, and loudspeakers—for which an admissible-position survey plays the same role, and it is the reason why the framework of Section 4 is described in terms of what it installs on the monument rather than only in terms of what it computes.

4. The Management Model and the IoT/IoE Technological Framework

The organizational foundation of the project is the integrated multidisciplinary model for security and safety management (IMMSSM) introduced in [5]: a management model in which security, safety, emergency and service processes are designed jointly, across disciplines, rather than delegated to separate technical silos. The model's practical value depends on the technological layer that implements it: an Integrated Technological System Framework (ITSF) based on the IoT/IoE paradigm, in which people (operators, personnel, visitors), things (sensors, cameras, mobile terminals, wearables), data (from all subsystems, aggregated and correlated) and processes (ordinary management, emergency procedures, visitor services) are interconnected through a common, layered infrastructure [10]. The IoT/IoE approach gives the framework the two properties that heritage sites need most: modularity (any evolution of the management model translates into a bounded reconfiguration of the framework rather than a redesign) and service convergence (the same infrastructure carries security, safety and visitor services, minimizing the number of physical installations on the monument). The architecture of the framework realized at the RPC is shown in Figure 3: three functionally separated wired networks (supervision/control/security; personnel; visitors) with firewalled interconnections, redundant protected servers, field-element layers and multiple redundant paths towards external networks.

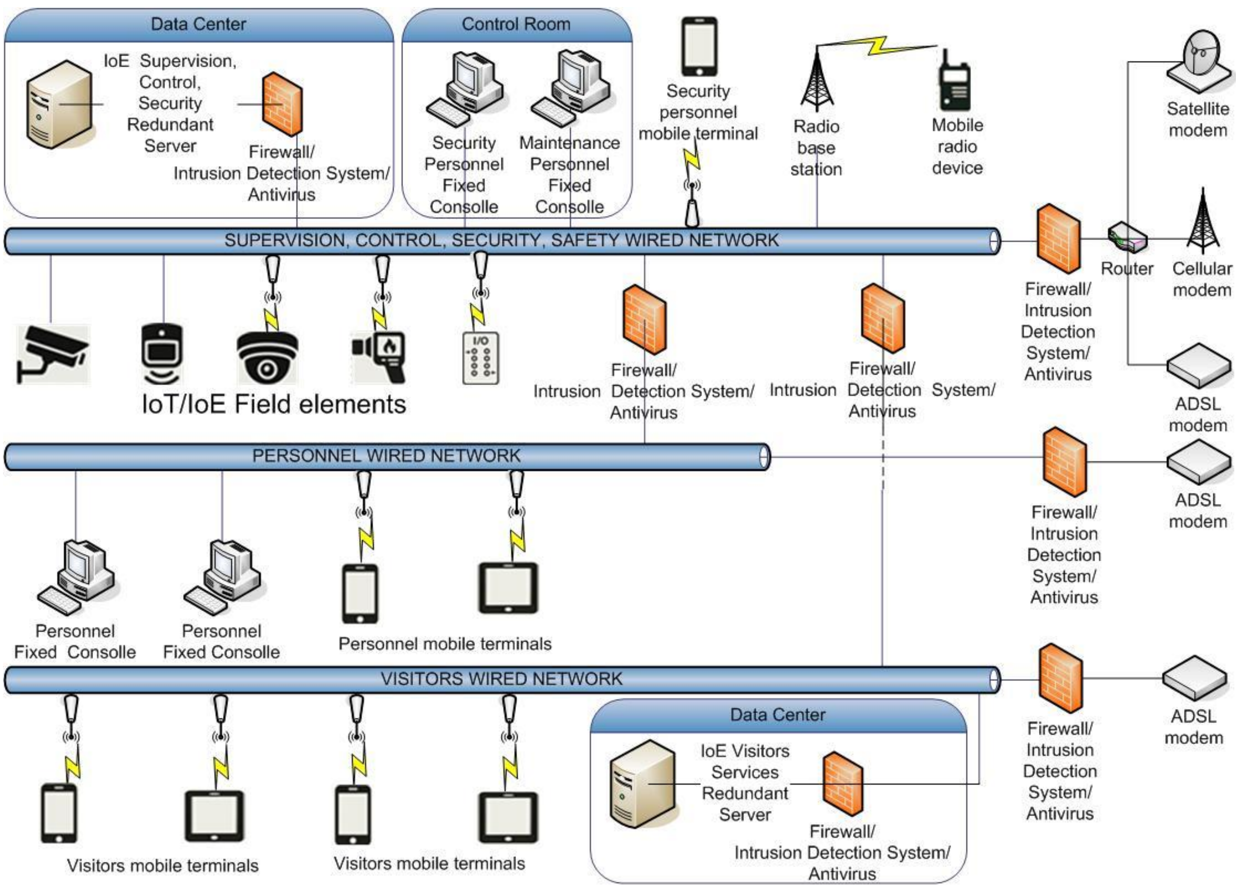

Figure 3. Architecture of the IoT/IoE-based Integrated Technological System Framework realized at the Royal Palace of Caserta.

5. The Realized Integrated System

The Safety and Security project of the RPC, started in 2019, realized the framework of Section 4 through the following subsystems.

Supervision: the Smart Mapping Interface (SMI). The integration point of the whole system is a 3D-map-based supervision platform through which every subsystem, device and installation (and, during operations, the position of personnel and the anonymized density of visitors) is monitored and controlled. The platform aggregates heterogeneous sources (video surveillance, access control, intrusion detection, seismic and hydrogeological monitoring, air quality) and presents them through a Natural User Interface designed for rapid comprehension in control-room conditions, generating alarms on threshold crossings, anomalous behaviours and critical situations.

Control room and data centre. A new control room was realized with specific attention to ergonomics and energy efficiency, together with a new data centre hosting the computing resources of the platform; the pre-existing control room is retained as a backup site, giving the system service continuity and disaster-recovery capability. Green-computing criteria (renewable energy sources and consumption optimization) guided the design, an aspect of growing importance for institutions that operate monumental complexes.

Communication network. A new telecommunication network extends across the whole park through autonomous nodes equipped with on-board UPS, able to operate during failures of the main power supply. Nodes connect through optical fibre on the long ranges and copper locally, and every field element (cameras, Wi-Fi access points, sensors, loudspeakers) attaches to the nearest node. The severe limitation of admissible installation places imposed by the aesthetic restrictions made the node-placement problem itself an optimization problem, addressed with the GA-based methodology previously developed for the Pompeii network [11]. A dedicated electrical power network, backed by generators, feeds the communication infrastructure. Over this network, a Wi-Fi service covers personnel and visitor needs.

Video surveillance. A new video-surveillance system protects the gardens and the long perimeter, combining visible-spectrum cameras and thermal cameras for night and long-range operation. All cameras carry on-board analytics for edge computing; all streams are additionally processed in the data centre for advanced functions. The number of cameras required by the extension of the perimeter, combined with the aesthetic restrictions on installation points, motivated the GA-based design method of Section 6.

Public address and radio communications. A public-address subsystem, based on compact high-power loudspeakers chosen to minimize visual impact and count, covers ordinary and emergency communication towards visitors across the gardens. A Digital Mobile Radio (DMR) subsystem, with standard and high-tier terminals, serves ordinary and emergency communications of security and safety personnel.

Artificial-intelligence engine. A processing layer based on big-data analysis, video analysis, data mining and blockchain-supported logging provides advanced and predictive functions over the aggregated data streams (from crowd-flow prediction to anomaly detection), closing the loop between sensing and management.

Visitor application and internal messaging. A mobile application supports visitors with map-based routing and information on points of interest; during the visit, and only during the visit, it transmits anonymized position data that allow the system to detect gatherings and presences in unauthorized areas. The application also lets visitors report critical situations, triggering, after verification, the corresponding recovery processes. An internal private-messaging system supports the site's operational communication.

6. Genetic-Algorithm Design of the Perimeter Video-Surveillance System

6.1. Problem Statement

This section formalizes the design problem outlined in Section 1. The perimeter of the RPC gardens must be covered by fixed cameras installed on brackets along the perimeter wall. A preliminary survey of the site provides: the set of existing brackets (positions where a camera can be installed with no new fixing); the set of positions where a new bracket may be admissibly installed; and the of bends of the wall, past which a camera's line of sight is interrupted. All positions are discretized at 1 m resolution along the curvilinear abscissa of the wall (total length L).

A camera installed at position x, aimed parallel to the wall, covers a stretch of wall whose length depends on its optics. Requiring a monitored corridor of width L_0 at the far end, the pinhole relation

$$f = w \times D/L_0 \quad (1)$$

links the focal length f, the sensor width w and the maximum distance D at which the corridor width is achieved; the covered length is therefore $\ell(f, w) = f \times L_0/w$, truncated at the first bend beyond x. With the commercial ranges $f \in [8, 135]$ mm (1 mm steps, 128 values) and $w \in \{3.2, 4.8, 6.4, 8.8, 12.8\}$ mm (the 1/4″–1″ formats), and $L_0 = 1$ m, coverage lengths range from sub-metric values up to ≈42 m.

The design problem is: choose the number of cameras, their installation positions (on EB or NB points only) and their optical parameters (f, w) so as to (i) cover the whole perimeter, (ii) minimize the number of cameras, (iii) minimize coverage overlaps, (iv) maximize the use of existing brackets and (v) minimize the number of new brackets (objectives (iv) and (v) encoding the aesthetic-impact constraint of Section 3). The problem contains the minimum-cost set-covering problem on intervals as a special case and inherits the NP-hardness of camera-placement formulations [40–43], motivating a metaheuristic approach.

6.2. Encoding

The reference camera number is defined from a practical minimum coverage length ℓ_min:

$$N\_min = round(L/\ell\_min) \quad (2)$$

Two observations fix ℓ_min. The literal worst case of the optical ranges (f = 8 mm on a 1″ sensor) yields $\ell = 0.625$ m; adopting it would inflate the chromosome by more than an order of magnitude while modelling configurations that no designer would deploy for perimeter protection. We therefore set ℓ_min = 10 m (corresponding, e.g., to f = 32 mm on a 1/4″ sensor) as an explicit design parameter and define the slot number of the chromosome as n·N_min with $n > 1$ (n = 1.3 throughout this work), leaving to the algorithm the task of deactivating the slots in excess.

Each slot is encoded by four genes totalling 25 bits (Table 2): the position gene (14 bits, 1 m resolution, range 0–16,383 m, sufficient for the 3 km scale of the site and extensible by adding bits); the focal-length gene (7 bits, 128 values, 8–135 mm at 1 mm steps); the sensor-format gene (3 bits mapped surjectively onto the five commercial formats, the three redundant codes remapping to the first formats so that no code is invalid); and the activation gene (1 bit). A chromosome (an individual I) is the concatenation of the n·N_min slots, for a total length of 25·n·N_min bits.

Table 2. Genes encoding each camera slot.

Gene	Parameter	Bits	Range/Values
1	Position x of the installation bracket	14	0–16,383 m (1 m steps)
2	Lens focal length f	7	8–135 mm (1 mm steps)
3	Sensor format w	3	1/4″, 1/3″, 1/2″, 2/3″, 1″ (surjective mapping)
4	Camera active	1	0/1

A decoded position that does not fall on an admissible point (EB ∪ NB) is repaired to the nearest admissible point if this lies within a tolerance d_tol (3 m in this work), the approximation rule that greatly improves the viability of random genetic material, and the slot is otherwise deactivated. Before the run, a feasibility check verifies that the admissible points are at least n·N_min; failing that, the designer is alerted to extend the NB survey, preventing runs that could not converge by construction.

6.3. Fitness Function

The fitness of an individual I is the weighted sum of five normalized terms:

$$f(I) = \alpha \times C(I)/L - \beta \cdot O(I)/L - \gamma \times N\_act(I)/(n \times N\_min) + \delta \times B\_EB(I)/|EB| - \varepsilon \times B\_NB(I)/N\_min \quad (3)$$

where C(I) is the covered length of the perimeter, O(I) the total overlap length, N_act(I) the number of active cameras, B_EB(I) the number of distinct existing brackets used and B_NB(I) the number of distinct new brackets used; $\alpha \ldots \varepsilon \in (0, 1]$ are design weights. The first term rewards coverage; the second and third penalize redundancy and system cost; the fourth rewards the reuse of existing installation points; and the fifth penalizes new fixings on the historical wall. Two specification details deserve emphasis, since the behaviour of the algorithm depends on them critically. First, the bracket terms must count distinct installation points, not cameras: counting cameras allows the population to accumulate redundant cameras on existing brackets, farming the δ reward without any benefit (a failure mode we verified experimentally). Second, the fifth term carries a negative sign: it penalizes, rather than rewards, the consumption of new brackets, in coherence with the aesthetic objective.

6.4. Genetic Operators and Convergence

The population (120 individuals in this work) is initialized randomly with three biases that mirror the designer's prior: a fraction of slot positions is forced onto existing brackets; activation genes are initialized sparse (30% active); and optical genes are biased towards long-coverage configurations. Selection is by tournament (k = 3); recombination is uniform crossover at slot granularity, which respects the building blocks of the encoding; mutation is bit-wise with rate 1/(chromosome length); and the two best individuals are copied unchanged into the next generation (elitism). At every generation, the position-admissibility control of Section 6.2 is applied to all offspring. Convergence is declared when the mean population fitness varies by less than a threshold p_stop with respect to its mean over the last N_G generations (N_G = 60, p_stop = 0.02% in this work), with a hard cap on generations.

7. Results

7.1. Experimental Setup

The method was characterized on synthetic perimeter instances designed to span the conditions of real sites: perimeter lengths L ∈ {250, 500, 1000, 2000} m; bends every ~150 m on average; existing brackets amounting to ~20% of N_min; and admissible new-bracket positions generated with density R ∈ {0.1, 0.5, 0.9} (the ratio between admissible new-bracket positions and perimeter length, which measures the freedom left to the optimizer by the site's restrictions). The characterization comprises the four campaigns detailed in Table 3, for a total of 311 genetic-algorithm runs; each of the 108 instances of the performance campaign was additionally solved with the two greedy baselines described below, bringing the reported executions to 527. A fresh instance is drawn for every run, except in the weight-sensitivity campaign, where the weights are swept on five fixed instances so that their effect is not confounded with the instance-to-instance variability. Every run is seeded deterministically from a single master seed, so that any individual run can be reproduced in isolation; the simulation code and the instance-generation parameters are provided as Supplementary Material. Unless stated otherwise, weights were (α, β, γ, δ, ε) = (1.2, 0.4, 0.55, 0.3, 0.3). This is the reference configuration adopted to characterize the method. The operational design of the RPC perimeter used the same objective function, with priority given to coverage on the stretches of the perimeter classified as critical by the risk analysis and residual gaps closed by patrol procedures (Section 8.1); in the terms of Equation (3) that choice corresponds to the high-α region of the sensitivity curves of Section 7.4. Two reference designs were run on the same instances. The first is coverage-only: sweeping the perimeter, it repeatedly installs, on the admissible point that extends coverage furthest, a camera with maximal reach—a near-optimal strategy for pure interval covering that ignores every objective except coverage. The second is bracket-aware: it installs a camera on every existing bracket and then closes the residual gaps with the same coverage-only sweep so that the existing installation points are reused by construction. The two baselines separate two effects that a single coverage-only reference conflates: the price of the heritage objectives as such and the price of pursuing them by joint optimization rather than by a two-phase heuristic.

Table 3. Structure of the simulation campaign.

Campaign	Figures	Design	Runs
Optimization performance	4, 8	4 perimeter lengths × 3 densities R × 9 independent instances	108
Convergence	5	L = 1000 m, R = 0.5, 8 independent instances	8
Weight sensitivity	7	5 values of α × 3 values of γ × 5 fixed instances	75
Normalization	6	4 reference camera numbers × 3 densities R × 10 independent instances	120
Total genetic-algorithm runs	—	—	311
Greedy baselines	8	Coverage-only and bracket-aware on each performance instance	216
Total reported executions	—	—	527

7.2. Optimization Performance

Figure 4 reports the final-to-initial camera ratio N_GA/N_min and the achieved coverage as functions of the problem size and of R. The ratio is stable at 0.36–0.40 across all problem sizes: the algorithm reduces the camera count to roughly one third of the reference number, consistently. The bracket availability R acts chiefly on the achievable coverage: with R = 0.5–0.9 the algorithm reaches 95–98% of the perimeter, while with R = 0.1 coverage saturates at ~91–92% (when admissible positions are scarce, stretches of wall simply cannot be reached, and no optimizer can compensate for an insufficient survey). Existing brackets are used almost completely in every condition (95–100%), confirming that the δ term drives the intended aesthetic behaviour. Convergence (Figure 5) required on average 120–410 generations, growing regularly with problem size.

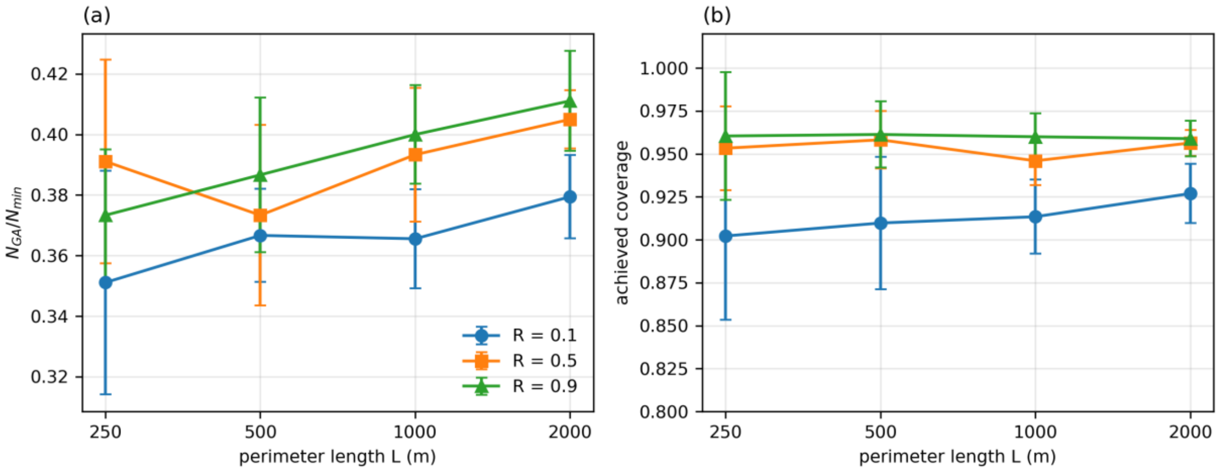

Figure 4. GA results versus problem size and new-bracket availability R (mean ± 95% CI over independent runs): (**a**) final-to-initial camera ratio; (**b**) achieved perimeter coverage.

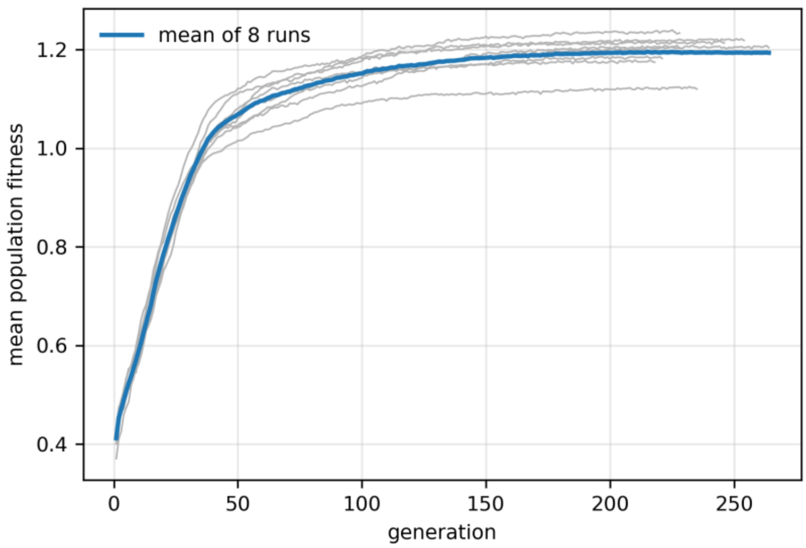

Figure 5. Convergence of the mean population fitness (L = 1000 m, R = 0.5; 8 independent runs and their mean).

7.3. The Role of the Normalization: Reconciling Two Views of the Same Behaviour

The ratio N_GA/N_min depends on how N_min is normalized. When N_min is anchored to the practical coverage length (Section 6.2), the ratio is essentially flat in problem size (Figure 4a). If N_min is instead defined with respect to a worst-case reference coverage (letting the reference length shrink, so that N_min grows while the physics of the optics bounds the real camera number), the same experiments produce the decreasing, asymptote-seeking curves of Figure 6: the ratio falls from ≈0.61 at N_min = 25 to ≈0.27 at N_min = 200 simply because the denominator grows faster than the physically constrained numerator. The two presentations are complementary rather than contradictory: the worst-case normalization displays the optimization gain over a naive dimensioning, while the practical normalization displays the absolute efficiency of the final design. We report both to make the method's behaviour fully transparent. The experiment of Figure 6 was run for the present work, on instances generated with the procedure of Section 7.1. It is not a reproduction of previously published data.

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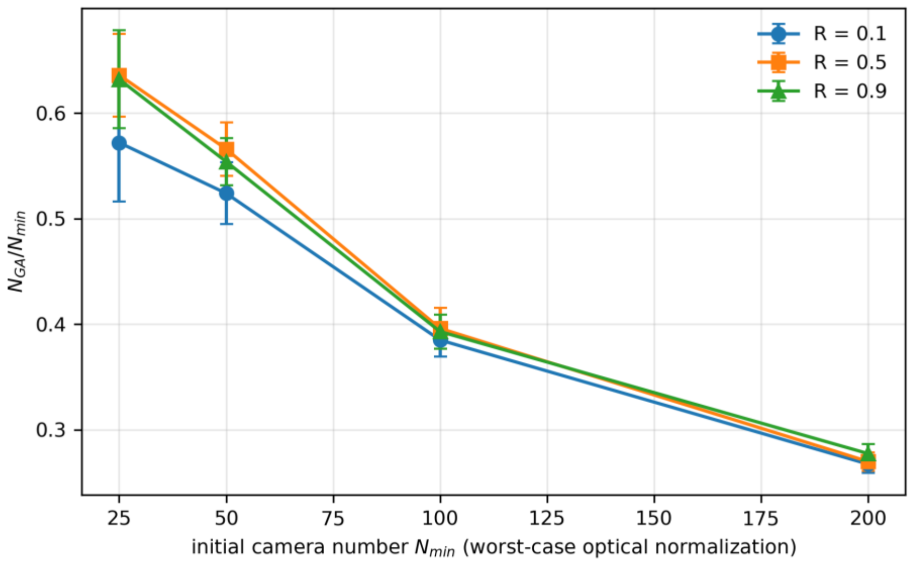

Figure 6. Final-to-initial camera ratio under worst-case normalization of N_min (L = 1000 m, three new-bracket densities R, mean ± 95% CI over 10 independent runs per point): the decreasing, asymptotic behaviour reflects the growth of the reference denominator against the physically bounded camera number.

7.4. Weight Sensitivity: The Coverage–Cost Trade-Off

Equation (3) aggregates conflicting objectives; its weights are therefore design levers, not nuisances. Figure 7 quantifies the two most consequential ones on fixed instances (L = 1000 m, R = 0.5): raising the coverage weight α from 0.8 to 2.0 raises coverage from ~93% to ~99%, at the cost of a camera ratio growing from ~0.35 to ~0.43; raising the camera-cost weight γ acts in the opposite direction. The designer can thus tune the α/γ pair to the site's priorities (full coverage at higher cost or bounded cost with declared residual gaps) with the sensitivity curves providing the exchange rate. In the RPC design, priority was given to coverage on the critical stretches of the perimeter, with residual gaps closed by patrol procedures.

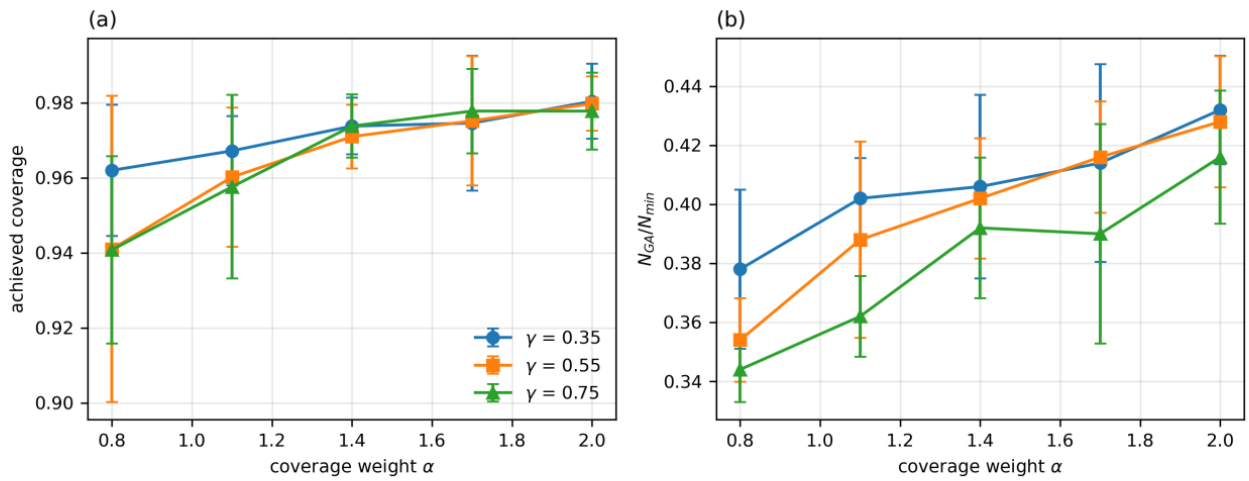

Figure 7. Sensitivity of the fitness weights (L = 1000 m, R = 0.5; mean ± 95% CI): (**a**) coverage and (**b**) camera ratio as functions of the coverage weight α, for three values of the camera-cost weight γ.

7.5. Comparison with the Greedy Baselines

Figure 8 compares the genetic algorithm with the two baselines on the same instances. Against the coverage-only baseline the GA installs more cameras: the overhead is 29–41%

when the runs are averaged by perimeter length, the aggregation shown in Figure 8a, and 18–48% when the twelve (L, R) configurations are taken separately. That overhead, however, is not the price of the metaheuristic. The bracket-aware baseline, which reuses the existing installation points by construction, pays the same price and slightly more: the GA uses 4.2% ± 1.7% fewer cameras than it. What the additional cameras buy, in both designs, is the reuse of the existing brackets—99% for the GA and 100% for the bracket-aware baseline, against 9% for the coverage-only one (Figure 8b).

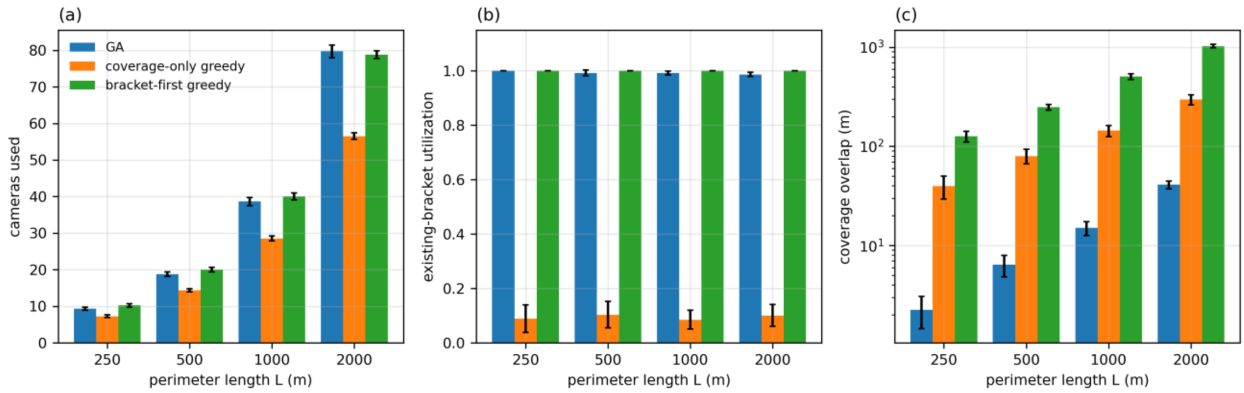

Figure 8. Genetic algorithm versus the coverage-only and the bracket-aware greedy baselines (mean ± 95% CI over the 108 instances of the performance campaign): (**a**) cameras used; (**b**) existing-bracket utilization; (**c**) coverage overlap, logarithmic scale.

The specific contribution of the joint optimization appears in redundancy. At equal bracket reuse the mean coverage overlap is 16 m for the GA, against 476 m for the bracket-aware baseline and 140 m for the coverage-only one (Figure 8c, logarithmic scale): the baselines buy coverage by blanketing the wall with maximal-reach optics, while the GA calibrates focal length and sensor format slot by slot. The GA also consumes slightly fewer new fixings (18.0 against 18.5 distinct new brackets on average). What it pays is 3.4 points of raw coverage (94.2% against 97.6%), a trade governed by the weights β and γ and quantified by the sensitivity curves of Section 7.4. Scored with the objective function it optimizes, Equation (3), the genetic algorithm ranks first on all 108 instances, with a mean fitness of 1.205 against 1.039 for the bracket-aware baseline and 0.937 for the coverage-only one.

This comparison also delimits the method's claim: on the pure covering problem a specialized algorithm is stronger, and on the reuse of existing brackets alone a two-phase heuristic is sufficient. The value of the genetic algorithm lies in the joint optimization of the heterogeneous objective set that heritage sites impose, which neither baseline addresses.

8. Discussion

8.1. Findings

The realized system shows that the IoT/IoE paradigm scales to a monumental complex of the size and sensitivity of the RPC: a single framework carries security, safety and visitor services, with the modularity needed to follow the evolution of the management model [5,10] and an invasiveness low enough to respect the site's constraints. On the methodological side, the simulation campaign turns the GA from a described technique into a characterized one: its optimization performance is stable across problem sizes; its behaviour under scarce installation-point availability is now quantified (and shows that the survey of admissible positions, not the optimizer, is the binding resource); its weight trade-offs are measured; and its cost with respect to a single-objective baseline is known. Two specification details identified in Section 6.3 (distinct-bracket counting and the sign of the new-bracket term) proved essential for correct behaviour, and their explicit statement should benefit any reimplementation. The comparison with the two baselines further separates two quantities that a single reference conflates: the number of cameras of the design is set by the heritage objectives themselves, since a bracket-aware heuristic pays the same price as the optimizer, whereas the quality of the design at equal bracket reuse—an order-of-magnitude reduction of coverage redundancy—is what the joint optimization of positions and optics contributes.

8.2. Limitations

The characterization is simulation-based: instances are synthetic, with randomized bends and bracket distributions, and the real RPC design involved site-specific constraints (view corridors, vegetation, listed-surface details) that enter the survey rather than the algorithm. The perimeter model is one-dimensional, with cameras aimed parallel to the wall (the appropriate abstraction for perimeter anti-intrusion coverage but not for area surveillance, which involves 2D visibility and occlusions [38,40]). Two further points concern the relation between the characterization and the realized installation. The parameters of the RPC perimeter design—the geometry of the admissible positions, the final camera layout and the residual coverage gaps—are not reported here, because for an operating high-value heritage site they are themselves security-sensitive; the synthetic instances of Section 7.1 were dimensioned to span the conditions of sites of this class, but they are not a substitute for the real geometry, and Section 7 should be read as a characterization of the method rather than as a report of the RPC design outcome. The vegetation of the gardens interacts with the one-dimensional model in a specific way: positions whose line of sight along the wall is obstructed by mature vegetation do not enter the set NB at all, while positions affected by seasonal growth were admitted only where a maintenance commitment on the corresponding stretch could be assumed. The adjustment is therefore performed at survey time and is invisible to the algorithm, which is one further reason why the quality of the survey, and not the optimizer, is the binding constraint identified in Section 7.2. The weighted-sum aggregation of Equation (3) yields one solution per weight configuration; a Pareto-based multi-objective formulation (e.g., NSGA-II-class algorithms [53,54]) would expose the whole coverage/cost front at higher computational cost and is a natural evolution of the method. Finally, the two baselines address, respectively, the covering objective alone and the reuse of existing brackets alone; no comparably general exact method exists for the full objective set, which is precisely the reason for the metaheuristic choice.

8.3. Transferability

Nothing in the framework or in the method is specific to the RPC beyond its parameters. The ITSF architecture has now been instantiated on an archaeological park [10], a museum [9] and a royal palace with monumental gardens; the camera-placement GA consumes only the outputs of a site survey (EB, NB, and BD arrays and the perimeter length) and a weight configuration expressing the site's priorities. For heritage administrations, the practical recipe the present work supports is: invest in the survey of admissible installation points (the R parameter is the binding constraint on achievable coverage); express aesthetic priorities as weights rather than as absolute prohibitions where possible; and require, from any optimization-based design, the statistical characterization (convergence, sensitivity, baseline comparison) that makes its claims verifiable.

9. Conclusions

This paper presented the IoT/IoE-based integrated security and safety system of the Royal Palace and Gardens of Caserta (supervision platform, control room and data centre, resilient park-wide network, video surveillance, public address, digital radio, artificial-intelligence engine and visitor services) and has formalized and characterized the genetic-algorithm method used to design its perimeter video surveillance under heritage constraints. The simulation campaign (311 optimization runs and 216 baseline runs) established stable optimization performance (final camera counts at 36–40% of the reference number), 95–98% perimeter coverage under adequate installation-point availability, near-complete reuse of existing brackets, quantified weight trade-offs and a measured 29–41% camera overhead with respect to a coverage-only baseline—the explicit price of protecting a monument without disfiguring it, which a bracket-aware baseline shows to be the price of the heritage objectives themselves rather than of the optimization, whose own contribution is an order-of-magnitude reduction of coverage redundancy at equal reuse of existing installation points. The framework and method are directly transferable to comparable heritage sites, and their evolution towards Pareto-based multi-objective optimization and 2D visibility modelling defines the research agenda ahead.

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Data Availability Statement: The simulation code implementing the method of Section 6, the instance-generation parameters of Section 7.1 and the scripts that reproduce the campaigns of Section 7 and Figures 4–8 are provided as Supplementary Material.

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Conflicts of Interest: The authors declare no conflicts of interest.

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