Decontamination strategies optimized for speed of reducing dangerous levels

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***Abstract*—We consider several scenarios of placement of endangered personnel or equipment in a contaminated zone where the contamination density is known and the contamination spatial effect decreases with the distance. A typical example is radiation contamination, where the radiation effect attenuates with the square of distance (geometric attenuation) and exponentially with distance due to air absorption. We assume that the decontamination means are characterized by the decontaminated area and linear speed. When the contamination density is known, algorithms for various scenarios can be determined for minimizing the total dose received by the rescued personnel. We exemplify the conditions for establishing the algorithm for optimal decontamination for several situations and show that, in general, evacuation paths should not be along lines.**

Keywords—contamination scenarios, radiation, decontamination algorithm; contaminant density, total dose, geodesic, point to curve distance

I. INTRODUCTION

Contamination may mean various things, including electronic virus contamination of information networks, soil, vegetation, houses, and hospital contamination with pathogen agents and parasites, and radiation contamination.

Decontamination strategies and their analysis were presented in several studies, among others by Babilas and Brendebach [1], Andersson [2], Roed et al. [3], Moria et al. [4], Yasutaka and Naito [5] for nuclear contamination, by Bewley (1986) [6] and by Sharp and Roberts [7] for microbiologically polluted land, by Krauter et al. [8] for bio-contamination, and by Fiochini et al. [9,10,11] and by Daadaa, Jamshed & Shabbir [12] for contaminated networks.

We deal with the decontamination of regions polluted with radioactive agents or other contaminants whose effect can be seen decreasing with the distance.

When decontamination time is of essence, the decontamination of planar areas with robotic means should take into account the effect of removing noxious materials on the level of radiation is specified points requiring maximal protection, for example points where personnel or critical equipment is trapped. We proceed as follows. First we present the general problem and various scenarios. Then, we present several simple yet not trivial examples to show that the straight line evacuation path is not advisable. Then we show how to transform the problem into one of geometry on surfaces and geodesics finding. One step further we show that the problem requires the determination of the distance from a point to a spatial curve along a specified surface. This general problem involves the corresponding geodesic. With this problem solved, we discuss sub-optimal solutions for decontamination, where the solutions depend on the number of available decontamination machines.

Throughout the paper we assume that the contamination degree is known; it may have been determined by flying drones above the area, or by an airplane with a good resolution collimator for the specific radiation, or by robots horoughly scanning the area.

We argue that any rescue team should have access to a software based on the exposed principles and algorithm or on a similar algorithm to quickly determine the best rescue path and recommend it to the rescued subjects, as well as for determining the best decontamination and rescue strategy to apply. The key references in solving the problem are Maekawa [13], Pottmann and Hoffer [14], and Patrikalaktis, Maekawa and Cho [15] who derived an efficient way of finding the distance from a point to a 3D surface, that is, the geodesic of minimal length between a point and a spatial curve.

In our case, the point is the initial position of the subjects to rescue, the 3D surface is the radiation function on the supposed planar terrain (or on a plane where the terrain projects), and the curve is the one delimiting the radiative zone, that is, an iso-irradiation curve of specified (acceptable) value of irradiation.

The second Section presents several scenarios of area of contamination and of positioning of the endangered subjects in the area and introduces criteria of optimization. The third Section we introduce the instantaneous radiation dose surface as a geometric equivalent of the problem; based on this, Section IV describes the geometrical equivalent of the optimal evacuation path. An elementary example is presented in Section V to help grasping the intuition of the problem and method. A further section (VI) provides an example on why the intuition may be wrong in guessing the best evacuation and decontamination path. The last section is conclusive.

II. SCENARIOS AND THE GENERAL PROBLEM

Several scenarios are considered, both in terms of decontamination means and threats. The scenarios for means include decontamination with a single device or team, decontamination with several devices or teams that can co-operate working either together in the same area, or choosing to operate in sections of the contamination zone / area at a distance.

Several simplifying hypotheses are made, although the algorithm can be extended to eliminate part of them. We consider total ease of deployment (zero installation / deployment time) and costs are not an issue. We assume that the decontamination is performed as a constant area rate (speed) and that the decontamination devices and /or teams are not affected by the contamination (operator dose null), such that the time spent by them in the contaminated area is not an optimization criterion. Complete knowledge of the contamination density in the area is assumed before the contamination process starts, as well as complete topographic information, including positioning of the places that must be protected; a planar area is considered as the basic case, while radiation obstructing non-planarities are dealt with as a separate case. Also, we assume that the effect of the contamination on the personnel or items to be protected is an integral of time, that is, a cumulative effect. The effect is assumed to decrease roughly with the square of the distance; a supplementary, exponential factor of radiation effect reduction is also considered to represent attenuation in the atmosphere of the contaminant effect (e.g., radiation). Radioactivity decay in time is disregarded. Finally, we disregard any scattering of the radiation and generation of secondary radiation in the atmosphere.

We show that, maybe counterintuitively, starting the decontamination at those points of interest and advancing along a line (shortest line segment) to the borders of the contaminated area may not be the most effective strategy. We describe the equations governing the decontamination strategy that minimizes the total SAR (Specific Absorption Rate).

III. THE INSTANTANEOUS RADIATION DOSE SURFACE

The first step in describing the problem formally is to determine the instantaneous dose in every point in the region of interest. The respective radiation dose (flux) is geometrically equivalent with a surface; the surface is continuous and its derivative is spatially continuous.

We denote by $\rho_r(x,y)$ the density of the contaminant in the region delimited by a border (curve) Γ, see Fig. 1.

The level of radiation at a point $P(x_0,y_0)$ in an area delimited by a border (curve) Γ is computed as

$$U(x_0,y_0) = \iint_{\mathrm{S}_\Gamma} C\cdot\frac{\rho_r(x,y)}{d^2\big((x,y),(x_0,y_0)\big)}e^{-kd((x,y),(x_0,y_0))}dxdy\ , \qquad (1)$$

where S_Γ is the contaminated surface delimited by Γ, $\rho(x,y)$ is the contaminant surface density, k is the attenuation constant in air, and C is a constant. The attenuation is exponential with respect to the distance. The air has a variable attenuation with respect of the energy W of the radiation, $k=k(W)$, see for example Day and Taylor [16]. Because the protected subject has a finite dimension, the distance is always larger than a minimal value, $d^2\big((x,y),(x_0,y_0)\big)\geq d_0$. Because of the geometric and absorption attenuations, the region close to the protected subject contributes a large part of the radiation dose.

With a decontamination speed assumed constant, expressed in surface decontaminated per second, $\Delta A/\mathrm{s}$, and with Γ^* the curve delimiting the cleaned region $\Delta\mathrm{A}$ at time t, the problem is equivalent with the choice of $\Gamma^*(t)$, that is, of its position, such that to minimize at the time moment $t+1$ the above surface integral for the remaining surface $\mathrm{S}_\Gamma\backslash S_{\Gamma^*}$. When the cleaning is only partial, the remanent radiation level remains to be accounted for in the above criterion; specifically, the best next step expression of Γ^*, $\Gamma^*(n+1)$, satisfies the condition

$$\Gamma^*(n+1)=\arg\max_{\Gamma^*}\big(U(x_0,y_0;n)-U(x_0,y_0;n+1)\big). \qquad (2)$$

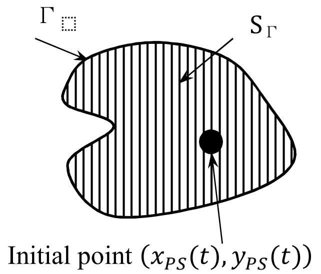

Fig. 1. Example of contaminated surface. Outside Γ, there is no radiation source. Inside the radiation source density is $\rho_r(x,y)$.

Practical restrictions apply; a typical one is the minimal increment of the decontaminated are, that is, minimal distance between the curves $\Gamma^*(n+1)$ and $\Gamma^*(n)$, imposed by the decontamination robot or equipment dimensions.

IV. THE GEOMETRICAL EQUIVALENT OF THE OPTIMAL EVACUATION PATH AND GENERAL ALGORITHM

When the evacuation is desired, one has to minimize the total radiation dose D_R received during the evacuation,

$$D_R=\int_0^T U(x_{PS}(t),y_{PS}(t))\,dl \qquad (3)$$

where T is the time until the evacuation is completed, $(x_{PS}(t),y_{PS}(t))$ are the coordinates (position) of the PS at time t. Notice that, while the density of radiation sources may be null outside a specified area (closed curve), one needs to compute the received dose $U(x,y)$ also far beyond that curve, because the subjects is irradiated significantly even at the exterior of the area where radiation sources are spread.

Throughout the paper we consider that the evacuation speed v is constant. Then, the integral D_R is equal with

$$D_R=\frac{1}{v}\int_0^\Gamma U(x_{PS}(t),y_{PS}(t))\,dl \qquad (4)$$

where dl is the length of the arc. When the end point is known, this is a problem of finding the geodesic between two points on the surface

$$z = U(x_{PS}(t), y_{PS}(t)) \tag{5}$$

The general problem is to find, for specified $(x_{PS}(t), y_{PS}(t))$, curve of final point, and U function, the best evacuation point and path. The optimization is difficult because of the intricate form of the function U and because of the indefinite end point. One can restate the problem as follows:

Find the shortest distance and the corresponding path (geodesic) from a point on a surface S_Γ to a closed curve Γ_0 of finite length but not necessarily convex, included in that surface, where Γ_0 is an equi-radiation curve of low radiation level where the subjects are deemed to be safe.

The above is equivalent with using the minimal path on the equivalent surface described by the radiation flux on the surface of the terrain, $U(x, y)$, where the initial point of the path is specified, (x_0, y_0), but the final point remains to be determined. We will consider that the final evacuation point is not restricted in any way, except that the radiation at the final point should be a specified value. In other words, there is an entire curve of equi-radiation where the evacuation point can lay on. The solution of the problem can be found only by approximate computations performed as in [13], [14], [15].

The discussion is applicable not only to disaster situations. It is valid also for space trajectories when the main concern is a travel with limited irradiation.

Several simplified methods for approximation and fast determination of an approximate shorter path are as follows:

i) Divide the interval $[0, U(x_0, y_0)]$ in K equal subintervals and determine for each value $j/K \cdot U(x_0, y_0)$, $j = 1 \ldots K-1$, the equi-radiation curves. Starting from (x_0, y_0) find the shortest path to the curve for $(K-1)/K \cdot U(x_0, y_0)$, then find the shortest path to it; repeat until $j = K$.

ii) Determine an approximation of U by a semispherical surface and then the difference surface by a set of spherical surfaces. Then find the paths with smaller lengths on the approximation so determined for U. If errors in surface approximations are large, continue approximation of the difference surfaces with sets of spherical surfaces until satisfactory approximation.

Another simplified method to find an approximate evacuation path is to evacuate along the gradient. However, this strategy is poor as shown in an example in the Appendix.

Once the shortest path is found, the best strategy for decontamination is to clean the path ahead of the evacuated subjects, when a single decontamination is available, or to clean in front of the evacuated subjects and simultaneously cleaning starting with the arrival point toward the evacuated subjects or as a third strategy, cleaning with both available machines a double large path in front of the subjects.

Example. In the simplified case of uniform contamination of a circular area around (x_0, y_0), the best strategy is to remove contamination at the closest points from (x_0, y_0). However, this is valid when the protected subject (PS) has to remain at (x_0, y_0). The evacuation path along a line segment is obtained in this case due to the axial symmetry of the contaminated area.

In this case, the best solution is to decontaminate the shortest evacuation path, if the decontamination speed v_D is fast enough compared to the maximum evacuation speed, v_E,$v_E > v_D$, where the width of the decontaminated path is as large as possible for the decontamination speed available. The reason for having a wide decontaminated path is clear in Fig. 1: at least a (possibly circular) region around the protected subject does not contribute radiation to the integrals above.

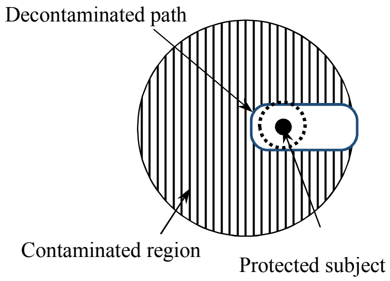

Fig. 2. Simple evacuation and decontamination solution in case of circular contaminated region.

Notice that in this study we assumed the contaminant fixed; partly airborne and wind transported contaminants were not considered; taking them into account dynamically changes the solution of the problem. However, when there is the possibility of predicting where the contaminant is transported in time, the same method as described can be applied.

Another limitation of the basic model used is that we assumed an infinite decontamination factor (DF), where DF is defined as "reduction in contamination (alpha or beta/gamma activity)" [17]. The same assumption is done for gamma radiation, with DRF defined as "reduction in gamma dose rate above a surface" [17] and DRF assumed very large. Typically, the decontamination factors for washing, sandblasting, hosing and/or sandblasting, digging, and removal of surface are between about 5 and 100, see [17]. However, the values in [17] are very different from those given in [18].

V. AN ELEMENTARY EXAMPLE

Consider that the contamination is along a thin strip and part of the strip is contaminated G times more than the rest. We choose the Ox axis along the contamination line and the origin at the border between the two regions, with the segment heavier contaminated at right. Then, neglecting the attenuation in the air, the subject at position $P(x, y)$ receives an irradiation R , $R(c, G, A, B; x, y) = \int_{-A}^{0} \frac{c}{(x+u)^2+y^2} du + \int_{0}^{B} \frac{cG}{(x-u)^2+y^2} du$, where c is a constant, A, B are the limits of the contaminated regions. Assuming that the initial position is for $x > 0$, the above becomes $R(c, G, A, B; x, y) = \int_{-A}^{0} \frac{c}{(x+u)^2+y^2} du + \int_{0}^{x} \frac{cG}{(x+u)^2+y^2} du + \int_{x}^{B} \frac{cG}{(x-u)^2+y^2} du$.

With appropriate change of variables, $v = x + u$, $v = x - u$, and of the limits of integration, the three integrals, having all

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the form $\frac{1}{y}\tan^{-1}\frac{v}{y}$, are computed. The similar idea of the greedy algorithm in continuous dimensions is the walk along the gradient, for a distance $\eta\frac{\partial R}{\partial x}, \eta\frac{\partial R}{\partial y}$. Notice that the integrals can easily be computed without a change of variable taking into account that $\int\frac{du}{(a+u)^2+b^2} = \frac{1}{b}\tan^{-1}\frac{a+u}{b}$ +ct. Thus, $R(c, G, A, B; x, y) = \frac{c}{(x)^2+y^2} - \frac{c}{(x-A)^2+y^2} + \frac{cG}{(B-x)^2+y^2} - \frac{cG}{(u)^2+y^2}$, which allows to determine in every point starting with the initial point the gradient and the path. Only when the initial position is on the Ox axis and outside the contamination interval, for symmetry reasons the evacuation path is along Ox.

The evacuation ends in a point of the curve $\frac{c}{(x)^2+y^2} - \frac{c}{(x-A)^2+y^2} + \frac{cG}{(B-x)^2+y^2} - \frac{cG}{(u)^2+y^2} = R_0$, where R_0 is a level of radiation deemed acceptable. The best evacuation path is along the geodesic of minimal length between the initial point and the above curve, on the surface $z = \frac{c}{(x)^2+y^2} - \frac{c}{(x-A)^2+y^2} + \frac{cG}{(B-x)^2+y^2} - \frac{cG}{(u)^2+y^2}$.

Depending on the initial position of the evacuation subject, the curve of the evacuation path and the position of the decontamination region differ: when the initial position is close to the segment with higher radiation source density, the move is first away from that segment (with small angle to the normal to the segment), see Fig. 3.

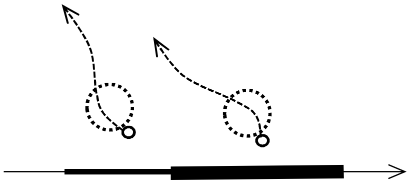

Fig. 3. Segments of line (radiative strips). The thick line denotes a stronger radiation (larger density of radiative sources).

VI. WHY INTUITION MAY BE WRONG

Consider that the (maximal) velocity of displacement of the PS is specified. Assume the contamination is uniform. Then, the path that runs away along a line from the contaminated region may be wrong, because the integral may be larger than for a curved path, see Fig. 7.

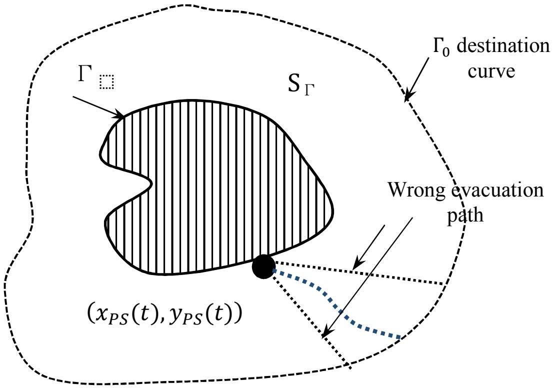

Fig. 4. Case of initial point at or close to the border of the radiated area: The straight lines are wrong evacuation path, with the total dose larger than the curved path.

If the path is along the curve Λ with a constant velocity v_{PS}, one has to minimize

$$\int_\Lambda \frac{dl(x,y)}{v_{PS}} U(x,y) \qquad (6)$$

Where the path Λ has as initial point the initial position of the PS, (x_I, y_I) and the final point is on the iso-radiation curve defined by $U(x,y) = U_{admissible}$ where admissible is a specified value; dl is the arc length along the curve Λ.

VII. DISCUSSION AND CONCLUSIONS

The presented scenarios, methodology, and algorithms apply to radiation decontamination; they can be adjusted for other contamination cases where contamination effects are inversely proportional to a power of distance between contaminants and victims, such as diffusion of contaminants. The method is not suitable for air transmitted, biological pathogens and other similar effects. Also, the method does not take into account the possibility of using radiation shields during the evacuation, as described for example in [19], for protecting the exposed subjects during rescue.

The criterion we used – minimizing the total received dose – is not the only possible one: in case of equipment, the resilience of the overall system may be of interest, as detailed in [20], [21], [22], [24].

Notice that some of the assumptions we made are only for sake of brevity of presentation and play no major part in the solutions put forward. For example, the hypotheses of the constant velocity of displacement of the protected subjects and the constant velocity of decontamination can be easily dropped – the first by using a weighted (by the normalized velocity of the subjects) squared distance. Even the hypothesis that the speed of displacement of the decontamination is larger than the speed of the subjects can be dropped with the addition of more computations.

Considerations for non-planar cases, i.e. cases where contaminated heights are more pernicious than contaminated valleys shielded by heights, were not presented, but for real cases the terrain effects have to be included in the computation of the surface $U(x,y)$.

A rescue team should be provided with computer applications based on the exposed principles and algorithm or on a similar algorithm to quickly determine the best rescue path; the path should then be communicated to the rescued subjects. Also, the software should be used by rescuers for determining the best decontamination and rescue strategy to apply. Such a software package is under development and will be discussed elsewhere.

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Appendix

Example of a radiation trap, when the strategy is to move along the descending gradient of the radiation intensity. Moving along the gradient one remains in a local minimum of radiation.

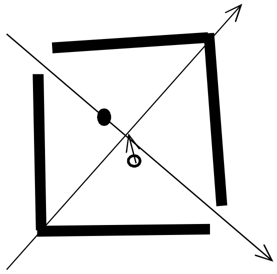

Fig. 5. Case of radiation trap for the walk along the descending (gradient) direction. The initial point is the black point; the circle is a local minimum of the function $U(x,y)$.