A GIS-based decision support system for the management of SAR operations in mountain areas

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Abstract

Information plays a basic role in decision making processes. In particular in the emergency management and SAR (Search and Rescue) operations, it is extremely important to take into account and use correctly as much information as possible to maximise the possibility of making the right decisions. Quite often decision makers do not consider all the available information. Moreover, cognitive biases cause several errors in the decision making process. These are some of the reasons that justify the effort for trying to build a decision support system, based on a normative approach to the decision-making, to manage mountain missing person search. Since cognitive biases influence the way the rescue squads act, and the environment affects the way a lost person thinks and moves, it is possible to start the design of a decision support system by trying to evaluate in a combined way both environmental and individual variables. The more natural and logical way to manage environmental information, i.e. geographical data, is to use GIS (Geographic Information Systems), while the best way to model the behaviour of lost people is to study the way they think and act. The implementation in a GIS allows the integration and the management of different kind of information.

The maximum speed of a missing subject is evaluated on the base of physiological variables and terrain features and it is used to evaluate the maximum reachable extent, thus defining the area the missing person can be found in. A map is built where isochronous lines are drawn around the last known position, defining the maximal search area for a given time. The model takes into account the morphological features of the searching area, the presence of physical obstructions to the lost person walk as well as preferential paths and some simple physiological parameters. The morphological parameters used are: height, terrain slope, vegetation density and the ground unevenness. Age, sex and training level of the subject are considered as physiological parameters. Visibility is another relevant parameter, accounting for the influence of light and darkness on the subject motion. Another important parameter that can strongly influence the lost person path is the presence of preferential paths or obstacles. It is possible to consider rivers as well as bridges, roads and mountain paths as elements influencing the velocity the lost person can or can not achieve. The model has been tuned on the few data available in literature and on walk speed estimates provided by professional mountain guides and by the “Aiut Alpin Dolomites” rescue corp. A GPS campaign has been carried out to

collect data to verify the results and the reliability of the model. A sensibility analysis has also been performed to evaluate the role and the relative influence of the different parameters of the model.

A GRASS module implementing the model is being built and will be released soon. Current developments include the development of a full DBMS approach, where all data, both semantic and cartographic, are stored in a spatial database. A web interface will be used both to feed the DBMS and run the model and to browse the model output and the database.

Moreover, a new approach is under development, where available power evaluated from the physiological parameter is matched against the energy cost required from the terrain features. In this way it will be possible to separate the effects of terrain features from missing persons parameters.

1. Introduction

Search and rescue (SAR) operations involve the use of massive human and technical resources but their effectiveness critically depends on the coordination and focusing of all the available means. Moreover, SAR campaigns must be planned and managed in real time after notice of missing person is issued. Today the experience of local operators plays a central role, since the knowledge of the area involved in the search is the most important factor in the operations planning.

This means that the quality of the campaign relies on real knowledge of the area of the local operators and, while the use of personnel's experience is positive, this introduces a significant degree of discretion.

The amount of geographic information and the power of managing and processing systems now available suggest the use of geographic information systems for all the operations involving spatial data. It is possible in this way to set up models to support SAR operations. The use of GISs allows:

- the combined use of all the available data, linked through their spatial attributes;
- the output as a set of maps, directly available to field personnel.

The basic idea is to combine all the available data on the search area and the information about the missing person to build a model indicating the search locations for the rescue squads. Two different classes of information must be combined: geographic data, describing the environment where the missing person is moving, and physiologic parameters, accounting for the missing's movement capacity. By combining these two types of information, a maximum travel speed is evaluated for the missing person's' movements for each cell into which the search area is discretized. In this way, it is possible to mark the maximum area travelled and therefore to indicate a search area at a given time after person's disappearance.

This model takes into account the presence of obstacles impossible to walk over (e.g. rivers), preferred routes (e.g. roads or tracks) and points where obstacles can be passed (e.g. bridges over a river).

This deterministic approach will be integrate with a stochastic model which, using data from previous rescue campaigns, can further restrict the search area by indicating the most probable locations for the missing person.

2. Speed evaluation

The model is built on the evaluation of the maximum speed a person can reach in an area, given his/her physical conditions.

Very few literature is available for such approach, most of SAR literature concentrates on probabilistic construction of location maps, on the dry land as well as in the sea, or on the study of lost persons behaviour [6].

There exist some attempts to evaluate the walking speed of pedestrians along tracks, mostly as support for alpine guides or tourist operators. An evaluation of the walking time along tracks as a function of slope is reported in [5] for a mean person: this can be useful for an estimation along the tracks but provides only a starting basis for the evaluation of speed outside the tracks, where terrain conditions and vegetation features must be taken into account. A first indication is that in one hour a normal person can gain 300 to 350 meters ascending and 400 to 600 meters descending, with a maximum speed of 4.5 Km/h on 5% descending slopes. However, no indication is given on how speed depends on the subject characteristics or on the terrain features.

The development of the speed model has been carried out in two steps:

1. identification of the relevant parameters;
2. evaluation of an analytical relationship between the subject speed and each parameter.

Some information can be inferred from literature studying the walking speed in particular conditions (e.g. indoor inside wide building or in an urban environment), building parallels between these situations and the movement of a person in an mountain area.

Several studies are available for the evaluation of the optimum street signal cycle length in urban areas [1], investigating the dependence of walking speed on several factors (functional street classification, vehicle volumes on the street being crossed, street width, weather conditions, number of pedestrians crossing in a group, signal cycle length, timing of the various pedestrian-signal phases, whether right turn on red is allowed, pedestrian signals, medians, curb cuts, crosswalk markings, stop lines, and on-street parking), however only some of these parameters can be useful for establishing a relationship with speed in mountain areas:

- sex;
- curb height, can be correlated to the unevenness of the terrain;
- meteorological and pavement conditions, this is actually not usable since in urban environment people tend to walk faster in adverse weather conditions, while in mountain areas the opposite behaviour is usual;
- temperature;
- wind intensity;

- walk duration.

Speed values are given with reference to percentiles of the tested subjects unable to reach such velocity, those corresponding to the highest percentile available (85%) have been used, since the model should evaluate the maximum possible speed.

Other studies regard the walking speed in airport terminal [3], developing a relationship between speed and people density, this can be used as a first indication of the connection between density of obstacles (notably threes) and walking speed in mountain areas.

The creation of a model for the maximum walking speed in mountain areas has been carried out in three phases:

- identification of the relevant parameters;
- writing of an analytical expression linking speed to the parameters;
- evaluation of the coefficients to match model results to empirical values.

The identification of the relevant parameters has been based on the literature findings and on experience of field SAR squads operators. The analytical expression for maximum speed has been kept as simple as possible, so that it is easier to evaluate the importance of each parameter and its numerical evaluation is fast. Finally, the evaluation of the coefficients has been carried out using literature values and field data from previous SAR campaigns. To verify these assumptions, a test campaign with GPS tracking of supposedly "lost" persons has been carried out.

The relationship between speed and the other parameters is written as

$$speed = slope \cdot height\_eff \cdot veg\_dens \cdot uneven \cdot age \cdot sex \cdot phfit \cdot weariness \cdot visib \quad (1)$$

where the parameters take into account the variation of speed with:

- *slope* terrain slope;
- *height_eff* height;
- *veg_dens* vegetation density;
- *uneven* terrain unevenness;
- *age* missing's age;
- *sex* missing's sex;
- *phfit* missing's physical condition;
- *weariness* missing's weariness as time passes;
- *visib* visibility at different day's time.

All the parameters above are adimentional but $slope$, which has the same dimension as the evaluated speed [km/h]. This simple formulation allows an easy calibration of the parameters as well as a simple analysis of the relevance of the uncertainty of each parameter on the reliability of the speed's estimate.

It is useful to separate the evaluation of the relationship between speed and physiological parameters of the lost person from the effect of terrain features.

2.1 Terrain features

Terrain features influence the walking speed with reference to terrain geometry and coverage. The main parameters describing the terrain geometry influence are slope and height. Ground coverage can be taken into account by the vegetation density and unevenness.

The first source for a relationship between maximum walking speed and slope is the 2d plot in figure ?? of [5], where isochronous lines are plotted against slope and distance. The shapes of the plots have been reconstructed with a set of eight second and third order polynomial expressions, on eight intervals between -90 (downward) and 90 (upward) degrees, extending the original range of [-40,-40] degrees.

The maximum speed of 4.5 km/h is reached for 5 degrees downward sloping terrain, while for slopes higher than 55 degrees speed decreases abruptly.

Height influence over human physiological parameters, and therefore walking speed, have been investigated in detail; human efficiency is mainly related to partial O_2 pressure, which influences the aerobic efficiency. For the purpose of this model a simple analytical relationship between walking efficiency and height is needed. From available literature [4] table 2 has been derived and its values has been interpolated with a third order polynomial.

Vegetation density has been taken into account extending data from [3], where maximum speed inside airport terminals is reported to usually reach its maximum when more of 2.3 m^2 is available for each moving person. A parallel for tree density has been made choosing a threshold of 0.4 trunks per square meter: below this density the vegetation is supposed to have no effect on walking speed. For densities above the threshold the *veg_dens* parameter has been chosen empirically as in table 3. For density values above the threshold but still close to it, the effect on the speed is supposed to be due to psychological "closure" feeling, while for higher density values vegetation constitutes a real obstacle. Psychological effects of vegetation on speed and direction are still under study and a more sophisticated model will be set up. This simplified model has been verified during the tests.

Terrain unevenness is a parameter often available from forestry inventories, where a value on a scale from 0 to 3 is given by the surveyor. No information is available in literature to derive a way to evaluate the relationship between terrain unevenness and walking speed, therefore an empiric expression has been built on values of table 4, checking its effectiveness during the tests.

slope [degrees]	efficiency
-90	0.05
-85	0.05
-80	0.05
-75	0.1495
-70	0.147
-65	0.1545
-60	0.172
-55	0.1995
-50	0.237
-45	0.60315
-40	0.6964
-35	0.82465
-30	1.0254
-25.3	1.31371915
-21.80140949	1.609941003
-18.26288994	1.994998316
-16.69924423	2.195961846
-14.5742162	2.602179154
-11.30993247	3.352974776
-6.842773413	4.481622731
-5.710593137	4.943857595
-2.862405226	5.268854447
0	4.9597
1.145762838	4.607412738
3.433630362	3.994252818
5.710593137	3.35794926
7.969610394	2.769005105
10.75796709	2.166047255
11.30993247	1.978832453
14.03624347	1.503571632
16.69924423	1.219351942
20.30447371	0.94794079
21.80140949	0.868819346
25	0.7558
30	0.6308
35	0.5098
40	0.4038
45	0.3128
50	0.2368
55	0.1758
60	0.1298
65	0.0988
70	0.0828
75	0.0818
80	0.05
85	0.05
90	0.05

Table 1: Relationship between slope and walking efficiency.

height [m]	efficiency
0	1
1000	0.975
2000	0.950
3000	0.900
4000	0.850
5000	0.750
6000	0.600
7000	0.400
8000	0.150

Table 2: Relationship between height and walking efficiency.

Plants' density	*veg_dens*	Area $[m^2]$
≤ 0.43	1	2.3 (1.51x1.51m)
$0.44 \div 0.47$	0.99	2.08 (1.44x1.44m)
$0.48 \div 0.57$	0.95	1.72 (1.31x1.31m)
$0.58 \div 0.69$	0.90	1.44 (1.20x1.20m)
≥ 0.70	0.85	≤ 1.44

Table 3: Relationship between vegetation density and the *veg_dens* parameter. The third column reports the area corresponding to each plant, for comparison with [3].

Terrain	unevenness grade	*uneven*
even	0	1
locally uneven	1	0.95
partially uneven	2	0.90
mostly uneven	3	0.85

Table 4: Relationship between terrain unevenness and the *uneven* parameter.

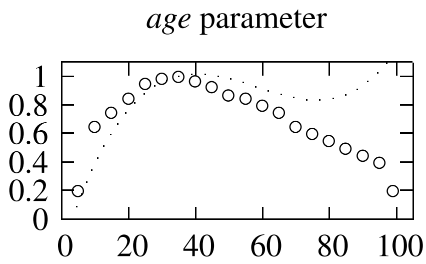

Figure 1: *age* parameter: experimental data ∘ and interpolating third order polynomial ·.

2.2 Physiological parameters

The physiological parameters of the missing person influencing the walking speed are age, sex and physical condition.

The relationship between age and walking speed has been derived from times of mountain running and off-track skiing races, as well as from data reported in [1]. Data consisting of duration times and ages from several races has been used, discarding anomalous entries. Age ranges from 20 to 60 years for athletes and from 13 to 75 in [1], since no other data is available the interpolating curve has been extended outside these boundaries but a experimental campaigns to fill this data gap are planned. The maximum speed is usually reached by 35 years old subjects: this age corresponds to value 1 for the *age* parameter, while the other ages yield lower values (figure 1). Empirical values are interpolated by the following polynomial:

$$age\ parameter = 8\ 10^{-6} age^3 - 1.4\ 10^{-3} age^2 + 7.4\ 10^{-2} age - 2.166\ 10^{-1} \quad (2)$$

with age in years.

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The relationship of walking speed with person's sex can be inferred from [1], [7], [2]. Mean speed for females is lower than for males: in the first study the difference is of 7.85%, in the second of 6.86% and in the third of 9.22%. The mean of these three values has been used, rounded up to integer: therefore speed is reduced of 8% for females with respect to males. Therefore the sex parameter is equal to 1 for males and 0.92 for females.

The physical condition parameter *phfit* is evaluated with reference to a mean person, as defined by ESPS (Ente Svizzero Pro Sentieri, Swiss Pro Tracks Board): a 40 year old male in good physical shape but without particular alpinistic or athletic capabilities. Persons are divided in four categories:

1. physically impaired;
2. sedentary, but in good physical shape;

Category	*phfit*
physically impaired	0.6
sedentary	1
irregular training	1.4
athlete	2

Table 5: Relationship between physical condition the *phfit* parameter.

3. performing irregular sport activity;
4. athlete (training at least four times a week).

Values for the *phfit* parameter are given in table 5, again from empiric evaluation.

2.3 Time dependent parameters

Two further parameters dependent on time affect walking speed: visibility and weariness.

Visibility accounts for speed reduction due to low or null visibility. Time in the model is evaluated by adding the elapsed time to the time the missing person has been seen for the last time. Three time intervals are used: sunrise to sunset, where speed is not affected by the *visib* parameter, which is equal to 1, sunset to total obscurity, when speed is reduced and the *visib* parameter is less than 1, and total darkness to sunrise, when the *visib* parameter, and therefore the walking speed, is set to zero. It is thus assumed that in total darkness the subject is not moving. It is difficult to evaluate the speed reduction due to light dimming, an estimate based on experience is of a reduction of 3%, i.e. a value of 0.97 for the *visib* parameter between sunset and total obscurity.

Weariness has the effect of progressively slowing down the missing's movement with time. To account for this, the *weariness* parameter is used. The walking speed is reduced by the *weariness* coefficient every hour from the starting time. It is possible to estimate a value for this parameter from [7] and [1] but the estimate of a loss of 8.5% of speed for an increment of 20% of walking time and of 10% after an increment of 80% indicates an unreasonably low effect of weariness on walking speed. Moreover, the parameter results to be independent from age.

Data from mountain running races indicate a slowdown between 5% and 10% each race hour, however this is true for athletes running at their maximum possible speed: it is therefore assume a speed decrement of 2% for athlete and higher values for the other categories of fitness condition, see table 6.

2.4 Speed evaluation for movement by ski or bicycle

Movement with ski or bicycle, as sometimes occurs for missing persons in mountain areas, obviously leads to different speeds, particularly on downslope terrain.

Category	*weariness*
physically impaired	0.90
sedentary	0.95
irregular training	0.95
athlete	0.97

Table 6: Relationship between physical condition the *weariness* parameter.

Skill	coefficient
low	0.5
medium	1
high	2

Table 7: Skiing skills coefficient.

Movement by ski results in higher speeds downslope and in slightly lower speeds upslope, due to the additional weight of the skis. While the speed reduction upslope can be considered independent from slope and skiing skills, downslope the speed increases with slope and skiing skills. Therefore, when moving by ski, a reduction of a 0.95 factor is applied for upslope movements, while downslope two parameters, which multiply formula 1, are used. The first parameter depends on the slope and is modelled using a third order polynomial whose coefficients have been evaluated from experimental data. The second parameter, accounting for skiing skills, is given in table 7.

In the case of movement by bicycle, speed is evaluated by modifying the expressions for the *slope* parameter, interpolating experimental values for cyclists. As for skiing, a further parameter accounts for the different driving skills for riders, but now the differences between low and highly skilled riders are supposed to be lower (see table 8).

3. Obstacles and preferred paths

When evaluating the speed of the missing person on a terrain, the existence of preferred paths, such as roads and track, and of insurmountable obstacles must be taken into account. In fact, roads and tracks

Skill	coefficient
low	0.75
medium	1
high	1.5

Table 8: Bicycle skills coefficient.

are usually the most probable locations where a person can be found , while obstacles limit the search area or, when passages are present, modify the time needed to reach an area. Moreover, the attainable speed on a road or on a track is significantly higher than on raw terrain. Therefore, on roads and tracks speed is multiplied by a factor greater than 1. This coefficient is set to 2 as a starting value and it is corrected during calibration.

Technical details on the algorithm that takes into account obstacles and passages are beyond the scope of this paper and are not reported.

4. Time maps

Walking speed is evaluated on a grid of suitable resolution around the point where the missing person has been seen for the last time, using equation 1 with parameters values given in section 2.. Using this speed it possible to build maps of minimum time to reach a point, keeping in mind observations of section 3.. Maps such as that in figure 2 are the main output of the model and are directly usable for planning and managing a SAR campaign.

Times are calculated as floating point values for each cell, but the result is given on a reclassified map with half an hour intervals, taking into account uncertainty on the speed, and therefore on the time, values, see section 6.. Graphical and topographic elements, such as roads, tracks, villages and rivers will be superimposed when the system will be in the operative stage.

5. Model calibration and tests

After series of tests to verify the correctness of the code implementing the model, the calibration of the model have been carried out using data for well known tracks, where records of travelling time and the parameters of section 2. exist.

Two areas in the Rabbi valley (Trentino region, Italy) have been selected for the tests. Furthermore, a dedicated survey campaign has been carried out, tracking a group of people with different ages, training levels, etc.

The first test is carried out by analysing time of movements along a mountain track which is 4000 meters long, and 0.6 m wide, with a total height difference of 1000 m. Times to cover the entire distance are known from alpine guides' experience.

Estimated time for a mean person, as defined by ESPS (a 40 year old male in good physical shape but without particular alpinistic or athletic capabilities), is of less than 2 hours, while experience indicates times between 2.5 and 3 hours. Tests with varying physical condition indicate that the *phfit* parameter is too high for the first two classes, therefore table 5 has been modified as table 9.

Test with varying age show an overestimate of walking speed for senior people, therefore equation 2 is modified:

$$\begin{cases} age\ parameter = -7\ 10^{-4} age^2 + 5.79\ 10^{-2} age - 1.352\ 10^{-1} & for\ age \leq 35\ years \\ age\ parameter = -6\ 10^{-5} age^2 - 4\ 10^{-2} age + 1.208\ 10^{-1} & for\ age > 35\ years \end{cases} \tag{3}$$

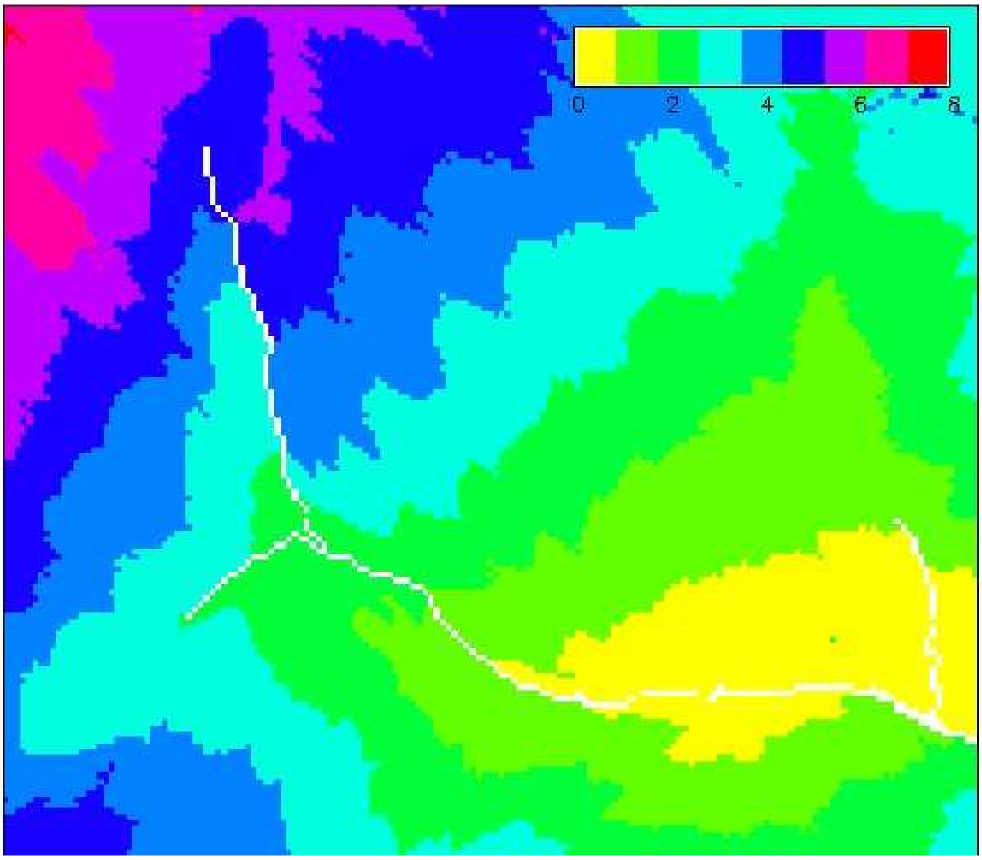

Figure 2: Map of the minimum reach time. Times are in hours, with half hour steps, the white line represents a road.

Category	*phfit*
physically impaired	0.5
sedentary	0.9
irregular training	1.4
athlete	2

Table 9: New relationship between physical condition the *phfit* parameter.

Times for females show an increment of about 8.5%, with good correspondence with the 8% speed reduction of the model.

The second group of tests is carried out in a mountain track with similar length but higher height difference, which is now of more than 1100 m, and larger width of 1 m. Results similar to those of the former test have been observed, but the time required to complete the distance is higher and the need to make the *weariness* parameter a function not only of time but also of age emerges, since slowing down for very young and very old people is more sensible that for other ages. Otherwise results of the model would not be realistic after 5 or 6 hours.

The analysis above is based on experience about mean times for different classes of persons, to rely on more precise data a GPS campaign ha been carried out, where people with different age, physical condition and sex have been tracked, recoding position and time. Age rages from 9 to 93 years, but for younger and older people assistance has been provided for safety reasons, therefore some of the data can be biased. Moreover, most of the people involved has tried to move as fast as possible because they knew they were tracked. While times show good accordance with model's results for ages between 20 and 30 years, for other ages speed is underestimated. This probably happens because most of the data used for calibration concerns people in the 20-30 yro range, while few data are available for people of other ages. To account for there results, table 1 is modified as table 10.

6. Sensitivity analysis

All the parameters used in the model are affected by errors, it therefore important to asses the uncertainty on the model's output. The error has been propagated analytically to evaluate the relevance of each parameter and its uncertainty on the precision of the localisation of areas' boundaries. The final analytical expression is quite complex, when evaluated for the maximum value of every parameter it yields to

$$\sigma_{vel}^2 = 10.32 \; [Km^2/h^2] \tag{4}$$

therefore, the RMS on the position of the areas as a function of time results of

$$\sigma_{pos} = \sqrt{10.32\, t} \; [Km] \tag{5}$$

The position error is of 805 m after 30 min and of 1600 m after 1 h, which is probably unacceptable for most situations. An analysis of the procedure shows that the training level *phfit* parameter plays the most relevant role, when the uncertainty on the training level is removed the accuracy increases remarkably:

$$\sigma_{vel}^2 = 0.38 \; [Km^2/h^2] \tag{6}$$

and the RMS of the boundaries is 150 m after 30 min, 305 m after 1 h and 460 m after 1.5 h.

slope [degrees]	efficiency
5	0.2
10	0.65
15	0.75
20	0.85
25	0.95
30	0.99
35	1
40	0.97
45	0.93
50	0.87
55	0.85
60	0.80
65	0.75
70	0.65
75	0.60
80	0.55
85	0.50
90	0.45
95	0.40
99	0.20

Table 10: New relationship between slope and walking efficiency.

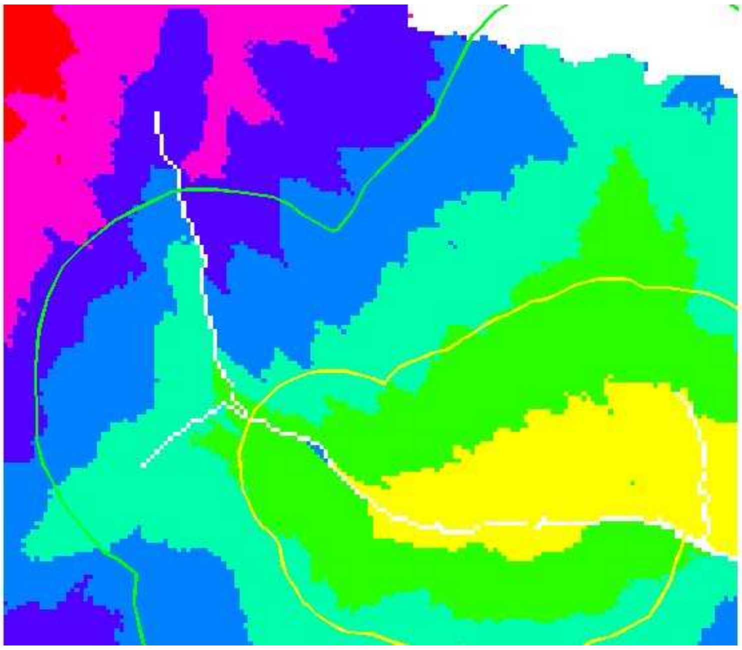

Figure 3: Map reporting the RMS of the first two areas (yellow and green), considering all the uncertainties.

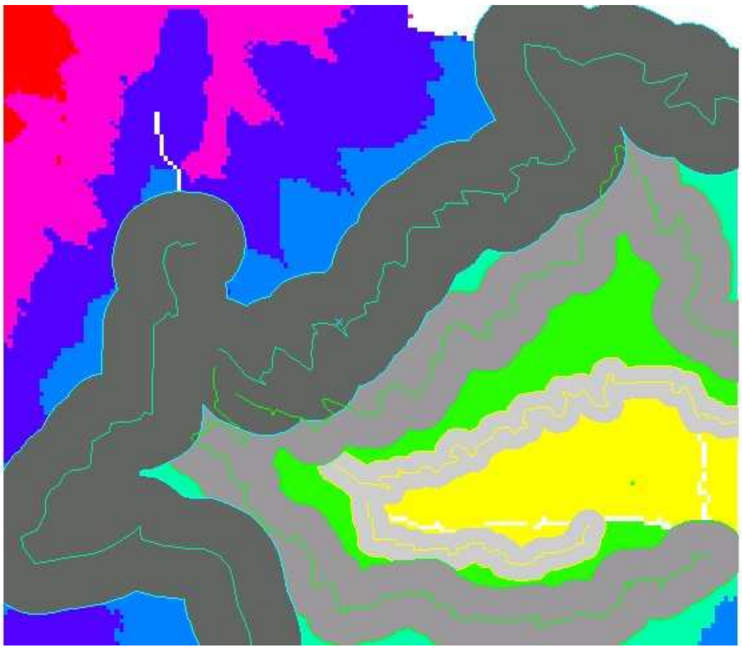

Figure 4: Map reporting the RMS of the first three areas, the *phfit* parameter is considered without error. The coloured lines represent areas' boundaries, gray bands the RMS around them.

7. Conclusions

This model will be one of the components of a more complete model for the support of SAR operations. The results of this deterministic approach will be coupled with a stochastic model: these two models will interact sharing the same input data and their own results. While the results reported in this paper are still preliminary, much work is being done both for model calibration and test and for the overall infrastructure.

The GIS model is working and the corresponding GRASS modules are ready, tests have been carried out successfully but more tests are due.

Current developments include the development of a full DBMS approach, where all data, both semantic and cartographic, are stored in a spatial database. A web interface will be used both to feed the DBMS and run the model and to browse the model output and the database.

The database structure is being set up and it is being feed with data. The web interface has been designed and is being coded. Moreover, the GRASS automatic execution via php is being implemented, the database structure is being improved to better separate persistent data (coefficients) from missing persons' data and the webGIS interface is being improved by adding cartography, adding new search tools such as place search by name and modifying the mouse coordinate capture widget. An automatic reporting tool is also being developed, while independent tests for the model are being carried out for different alpine region.

Other developments are planned but work is still to be done:

- the inclusion of behavioural models and psychological parameters in the deterministic model the GIS stochastic model;
- more extensive model tests;
- real life applications testing the overall feasibility of the system;
- real time units tracking (available from proprietary software vendors).

Collaborations with other research groups are being defined to address these issues.

A new GRASS modules have been written to implement the search model. The modules are being tested and will be made available when ready.

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