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Effective Heuristics for the GPS Survey Network of Malta: Simulated Annealing and Tabu Search Techniques

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Abstract

A GPS network can be defined as a set of stations, co-ordinated by a series of sessions formed by placing receivers on the stations. This paper shows how to search for the best order in which to observe these sessions giving the cheapest schedule. The complexity of observing GPS networks increases with their size and become highly difficult to solve effectively. To obtain good methods to solve this problem a new area of research is implemented. This area is based on developed heuristic techniques that provide an optimal or near optimal solution for large networks. Comparing their outcome in terms of solution quality and computational effort proves the performance of the developed techniques.

Key Words: combinatorial optimisation problem (COP), global positioning system (GPS), heuristic, simulated annealing (SA) and tabu search (TS)

1. Introduction

The US Department of Defence originally developed the NAVSTAR Global Positioning System (GPS) for military purposes. However, it has also been available for civilian users since the beginning. The GPS operational constellation consists of 24 satellites orbiting the earth (see figure 1) and provides the user with a 24-hour highly accurate three-dimensional position and timing system at any global location. The system is complicated but the idea is simple. Satellites are orbiting the Earth as known reference points and the unknown position of ground GPS receivers have to be determined. The satellites continuously transmit information on their positions and the receivers are able to measure their distance from the satellites at any time. If there are enough visible satellites the position of the receiver can be computed. The precision of these co-ordinates depends on several factors such as the satellite orbit accuracy and the errors of the distance measurements, and it is subject to the artificial degradation of the signals by the military (Leick, 1995; Saleh, 1996). The

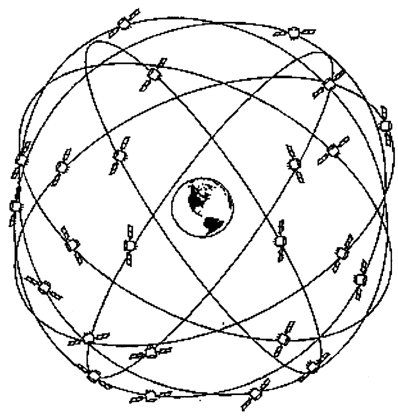


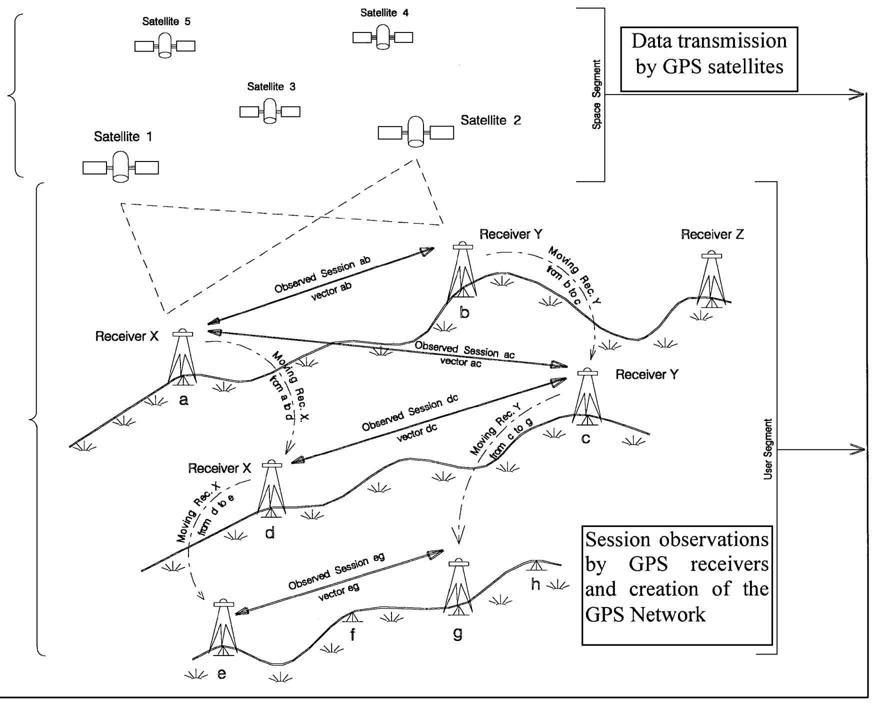
Figure 1. GPS satellite constellation (from Elliott, 1996).

above processes, which are involved in GPS surveying, provide unprecedented accuracy at an economical rate compared to other surveying techniques. On the other hand, using the GPS technique is highly expensive and this becomes crucial as the amount of work increases for large networks. To maximise the benefit of using this system, a new area of research that tries to provide near-optimal solutions for large networks within an acceptable amount of computational effort has been implemented. This research is based on heuristic techniques within the field of Operational Research (OR) (Saleh and Dare, 1997a, 1997b; Dare and Saleh, 1997). These techniques have been developed to allow the formulation of a strategy for designing GPS networks, which maximise the GPS technology benefit by reducing the total cost of carrying out the work.

This paper modifies and applies new heuristic techniques and investigates their performance to the GPS surveying problem. Section 2 describes the GPS problem as a Combinatorial Optimisation Problem (COP). Section 3 reviews the relevant literature of exact algorithms applied to GPS surveying networks. In Section 4 the new Simulated Annealing (SA) and Tabu Search (TS) methods are discussed and their basic structures for a GPS surveying network are formulated. Testing of the developed algorithms takes place in Section 5 by comparing their performances with results obtained using exact methods. Also in Section 5 comparisons of the heuristic solutions are presented. The paper ends with conclusions and some remarks. Also for future work, another heuristic algorithms are recommended on the basis of the performance comparison.

2. The formulation of the GPS survey network problem

The GPS network problem can be described as follows. There is a set of sub-schedules $J = \{1, \ldots, j\}$, a set of receivers $R = \{1, \ldots, r\}$, and a set of stations $N = \{1, \ldots, n\}$. Each sub-schedule consists of a sequence of sessions U, each of which uses a certain number of receivers (minimum of two receivers) to record satellite signals simultaneously for a fixed duration as shown in figure 2. Surveyors use at least two receivers to help eliminate many



No.	Session	Receiver X at:		Receiver Y at:		Receiver Z			Session Cost
		Station	Moving Cost	Station	Moving Cost				
1	ab	a	[- -]	b	[- -]				- -
2	ac	a	[0]	c	[C_{bc}]				C_{bc}
3	dc	d	[C_{ad}]	c	[0]				C_{ad}
4	eg	e	[C_{de}]	g	[C_{eg}]				$C_{de} + C_{eg}$
The Total Cost of the Schedule									Σ C_{ij}

Figure 2. Observation of Sessions using GPS receivers.

Figure 3. The Wild GPS System 200 receiver.

sources of errors (Teunissen and Kleusberg, 1998). Each receiver (X, Y, Z, etc.) can observe at most one station (a, b, c, d, e, f, etc.) at a time. A typical GPS receiver for such use is the Wild GPS System 200 receiver as shown in figure 3.

Given that a schedule is an ordered list of sessions, the problem addressed is to search for the best order in which these sessions can be organised—this gives the schedule of minimal cost to complete all the sessions. In practice this means determining how each GPS receiver should be moved between stations to be surveyed in an efficient manner taking into account important factors such as time, cost etc. To represent the GPS surveying problem within the frame of heuristics, the following notations are used:

J: the set of sub-schedules $J = \{1, \ldots, j\}$;
N: the set of stations $N = \{1, \ldots, n\}$;
n: the number of stations;

R: the set of receivers $R = \{1, \ldots, r\}$;
r: the number of receivers;
U: the set of sessions (sessions with 2 or 3 receivers) $U = \{1, \ldots, u\}$;
u: the number of sessions;
S_i: the set of stations visited by receiver i;
V: a feasible schedule which contains all the sub-schedules.
$C(V)$: the cost of schedule V;
Q: the universe of potential schedules $Q = \{1, \ldots, V\}$;
I: the size of neighbourhood;
C^i_{ab}: the cost of moving receiver i from station b.

The aim is to determine the optimal solution that minimises the total cost of observing the whole network and satisfies the requirements of GPS surveying i.e.,

$$\begin{aligned}
&\text{Minimise:} \quad C(V)\\
&\text{Subject to:}\\
&\qquad V \in I, \qquad I \subseteq Q;\\
&\qquad \textstyle\bigcup_{i=1}^{r} S_i \geq N;\\
&\qquad C(V) = \textstyle\sum_{i \in S_i} C(S_i); \qquad \forall i \in R.
\end{aligned}$$

An original cost matrix is constructed which represents the cost of moving a receiver from one point to another and computed based upon the criteria to be minimized. For example, as shown in figure 2, the cost of observing session *ac* after observing session *ab* is obtained by the cost associated by moving receiver Y from station **b** to station **c** while receiver X remains at station **a**. Subsequently, the cost of observing session *dc* is obtained by the cost associated by moving receiver X from station **a** to station **d** while receiver Y remains at station **c**. The cost could be evaluated purely upon time or purely upon distance, for more details about the evaluation of the cost matrix see Dare (1995). The cost to move between points will generally vary as this depends upon the distance between the points.

The GPS network problem is considered as a particularly hard combinatorial optimisation problem (Dare, 1995). Since it has highly practical applications, several exact and approximate algorithms have been proposed to find optimal and near-optimal solutions for it. For large networks, exact solution algorithms, based on a branch and bound method, are time-consuming in finding optimal solutions and difficult to program. On the other hand, heuristic techniques are a good alternative as they are easy to program and their implementation generally obtains good solutions quickly.

3. Exact methods (optimal solution)

A method for the optimal design of GPS networks, within the OR field, was developed by translating the schedule design problem into a Travelling Salesman Problem (TSP) and solving it using a mathematical programming technique (Dare, 1995). The requirement for the optimal solution of the TSP is to find the optimal route through the points based upon the supplied cost matrix. The TSP solution algorithm was developed upon an existing branch and bound approach but modified to take into account the more complex problem such as using more than one receiver and allowing for more than one working period (Multiple Travelling Salesman Problem, MTSP).

The following basic steps were followed for obtaining the optimal solution: (1) reduce the cost matrix (2) compute penalties (3) select largest penalty (4) delete rows and columns (5) repeat as necessary (6) backtrack to check other branches of the tree. The optimal schedule for a network consisting of four points and six sessions was obtained using the algorithm which enables the optimal solutions to be found without investigating every possible solution. Many examples of similar networks with optimal results can be seen in Dare (1995). However, this approach is limited to relatively small networks.

To provide a suitable method to solve large networks, the field of heuristic techniques has been investigated. Exact algorithms, which are procedures stated in mathematical terms, can solve only small networks and are not practical as the size of the network increases. Hence, it is crucial to have approximate algorithms which can provide an optimal or near-optimal solutions for large networks in a reasonable amount of computational time and with reasonable storage space requirements.

4. Heuristic techniques

Recently, heuristic approaches within the field of OR have been used successfully to find near optimal solutions to complex real-life problems in a reasonable amount of time. The key objective of this paper is to find an effective solution in a short period of time with close to least cost for a given GPS surveying problem using Simulated Annealing (SA) and Tabu Search (TS).

4.1. The simulated annealing (SA) algorithm

SA is a heuristic method that has been implemented to obtain good solutions of an objective function defined on a number of discrete optimization problems. This method has proved to be a flexible local search method and can be successfully applied to the majority of real-life problems (Kirkpatrick et al., 1983; Aarts and Van Laarhoven, 1985; Cerny, 1985; Osman and Potts, 1989; Rene, 1993; Dowsland, 1995).

In order to implement SA for GPS network design, a number of decisions and choices have to be made. Firstly, the problem specific choices, which determine the way in which the GPS network is modelled in order to fit into the SA framework. In other words, it involves the definition of the solution space (Q) and its neighbourhood structure (I), the form of the cost function $C(V)$ and the way in which a starting solution (V) is obtained. Secondly, the generic choices which govern the workings of the algorithm itself, are mainly concerned with the components of the cooling parameters: control parameter (T) and its initial starting value, the cooling rate (F) and the temperature update function, the number of iterations between decreases (L) and the condition under which the system will be terminated (Reeves, 1993). The performance of the achieved result is highly dependent on the right choice of both specific and generic choices.

The GPS-SA procedure used in this work is designed and developed essentially from practical experience and the requirement of the GPS technique. A simple constructive procedure is proposed to obtain an initial feasible schedule (V) for the GPS network. The aim of this simple procedure, which was implemented as a greedy local search method, is to obtain quickly an initial schedule. For more details about this procedure see Saleh and Dare, (1997c). The structure of the GPS-SA algorithm is shown in figure 4.

4.2. The tabu search (TS) algorithm

In this section, the GPS-TS procedure is described and a detailed step-by-step outline is given. TS, which is introduced by Glover (1989, 1990), is a procedure using ideas from Artificial Intelligence (AI). This procedure guides Local Search (LS) methods to overcome local optimality and obtain near-optimal solutions for hard combinatorial optimisation problems. According to Glover and Laguna (1997), Taillard (1994) and Osman (1993) TS is defined as the method based on procedures designed to cross boundaries of feasibility or local optimality, which were previously treated as barriers. A fundamental element underlying TS is the use of two certain forms of flexible memory to control the search process.

In the first stage, the process is carried out using short-term memory functions. These functions forbid moves that reinstate certain attributes of past accepted solutions. Attributes that are not permitted to be reinstated are called tabu and maintained in a short-term memory by a list called the tabu-list. Of course, it may happen that an important move is tabu. Nevertheless, in order to perform such a move, an aspiration criterion must be defined: this criterion evaluates the profit in taking a forbidden move. If this profit is acceptable, then the tabu status of the move is dropped and the move can be performed. There are, however, other possible aspiration criteria which can prove effective for improving the search.

In the second stage, the search is carried out among a subset of potentially good solutions and then redirected to a new region in the solution space, which might not yet have been explored. Exploitation and intensification strategies interact to provide fundamental cornerstones of long term memory in TS. Finally, the adopted stopping criteria in this algorithm is based on a given number of iterations or on the maximum number of iterations allowed without improving the best solution obtained so far. For more details about other advanced and more sophisticated elements of TS the reader is highly recommended to consult Glover and Laguna (1997).

TS has been applied to several COPs whose applications range from graph theory to general pure and mixed integer programming problems (Glover, 1995). The achieved success of TS in all the above applications is due to its implementation as problem-oriented. Thus, it needs, for each implementation, particular definitions of structural elements such as move,

[I] <u>THE PROBLEM SPECIFIC DECISIONS</u>

(A) *FORMULATING* the original cost matrix:

Step 1 Insert set of stations N.

Insert the estimated cost for each receiver's move C^{i}_{ab}

(B) *CREATING* the actual cost matrix (solution representation):

Step 2 Insert set of receivers R.

Define the sessions to be observed U.

(C) *DETERMINING* an initial schedule:

Step 3 Generate a feasible solution V cost C(V) using the actual cost matrix.

[II] THE <u>PROBLEM GENERIC DECISIONS</u>

(D) *INITIALIZING* the cooling schedule parameters:

Step 4 Set the initial starting value of the temperature parameter, T >0.

Set the temperature length, L.

Set the cooling ratio, F.

Set the number of iteration, K=0.

[III] <u>THE GENERATION MECHANISM</u>

(E) *SELECTING* and acceptance strategy of generated neighbours:

Step 5 Select a neighbour V' of V where $V' \in I(V)$.

Let C(V') = the cost of schedule V'.

Compute the move value $\Delta = C(V')-C(V)$.

Step 6 If $\Delta \leq 0$ accept V' as a new solution and set V=V'.

ELSE $\Delta>0$.

IF $e^{-\Delta/T} > \theta$ set V=V', where θ is a uniform random number $0<\theta<1$.

OTHERWISE retain the current solution V.

(F) *UPDATING* the temperature:

Step 7 Update the annealing schedule parameters using the geometric cooling schedule $T_{(k+1)}=F\ T_k$ {k=0,1,2...}.

(G) *TERMINATING* the solution:

Step 8 IF the stopping criterion is met THEN,

Step 9 Show the output.

Declare the best solution.

Declare the computation time.

OTHERWISE.

Go to (E).

END.

Figure 4. The general framework for the GPS-SA procedure.

neighbourhood, memory structures, aspiration function, stopping criteria, and the initial solution. Also, some values of several tuning parameters such as Tabu List (TL), Candidate List (CL) and Tabu Tenure (TT).

In this paper, a TS algorithm for GPS networks is proposed. Its structural elements will be defined in the following section, while results of computational tests will be discussed in

[I] INITIALISATION:

(A) *FORMULATING* the original cost matrix:
Insert set of stations N.
Insert the estimated cost for each receivers move C^{i}_{ab}

(B) *CREATING* the actual cost matrix (solution representation):
Insert set of receivers R.
Define the sessions to be observed U.

(C) *DETERMINING* an initial schedule:
Generate a feasible solution V cost C(V) using the actual cost matrix.

(D) *INITIALIZING* the Tuning Parameters:
Set the Tabu List TL (fixed or variable);
Set the Canditate Length, CL;
Set the Tabu Tenure, F;
Set the iteration counter, K=0.

[II] SELECTION STRATEGE AND ACCEPTANCE STRATEGY:

(E) *SELECTING* the best admissible move $C(V_{best})$:
Generate I neighbours of V_{int}, I={V1,.., Vn};
Create a CL for V_{int} using I;
Improve V_{int} into V_{best} with $C(V_{best})$.

(F) *UPDATING* the Tuning Tabu parameters:
Build up the TL by adding TL=[$C(V_{best}$,..];
V_{best} become the best new solution and the process continues;
Update the Counter K=K+1.

[III] THE STOPPING RULES:

(G) *TERMINATING* the algorithm:
Stop if the stopping criterion is satisfied;
Given number of iterations, OR
Maximum number of iterations allowed without improving the best obtained schedule.
OTHERWISE.
Go to (E).

(H) *DECLARING* the output:
Declare the best solution;
Declare the computation time;
END.

Figure 5. The general framework for the GPS-TS procedure.

Section 5. By considering the above principles, the basic GPS-TS algorithms can be written as shown as in figure 5.

The algorithm stops when the stopping criteria are satisfied. TS may adopt various stopping criteria (Glover and Laguna, 1997; Hertz and De Werra, 1990; De Werra and Hertz, 1989). The simplest is to stop after a defined number of iterations.

5. Computational results

It is most desirable to test and evaluate the proposed heuristic algorithms by comparisons with optimal solutions in respect to the solution quality and computational effort. The best known solutions obtained for the GPS surveying problem were those determined using a modified TSP algorithm and therefore computing the optimal value (Dare, 1995). A common measure to decide on the quality of a heuristic solution V_{heur} is the relative percentage deviation from the optimal solution V_{best}. The Relative Percentage Deviation (RPD), which is taken as performance measure, is computed as follows:

$$\text{RPD} = 100 \times \left\{ \frac{V_{\text{heur}} - V_{\text{best}}}{V_{\text{best}}} \right\}$$

The near-optimal schedules obtained using GPS-SA and GPS-TS heuristic techniques had the same result as the known optimal solutions (Saleh and Dare, 1997c, 1998a, 1998c) giving an RPD of zero.

The neighbourhood sequential search structure for generating new schedules as described by Lin (1965) has been adopted. In this structure, which is based on sessions-interchange, the potential pair-swaps are examined in the order (1, 2), (1, 3), ... , (1, n), (2, 3), ... , ($n-1$, n), (1, 2), etc. The change in cost is computed and the swap is accepted or rejected according to the acceptance strategy of the implemented GPS-heuristics techniques. This strategy examines the schedules in the generated neighbourhood of the current schedule and accepts the best one according to a given acceptance criterion. Both the GPS-SA and GPS-TS techniques were tested on hypothetical and actual GPS networks with known optimal schedules obtained using the MTSP (Dare, 1995). From the above, the ability of the developed GPS-heuristic techniques to generate, rapidly, high-quality schedules for designing the GPS networks can be seen.

To generalise the above developed procedures and work with larger networks, the data set for a network in the Republic of Malta spanning the islands of Malta, Gozo and Comino has been implemented. The GPS data and operational requirements for the session's observations were obtained from Dare (1994). The data set composed of 38 sessions, which comprised two weeks of session observations during July–September 1993, covering the Malta GPS network of 25 stations as shown in figure 6. Each session uses a certain number of receivers, the first 22 sessions were observed using two receivers R_1 and R_2 while the second 16 sessions were observed using three receivers R_1, R_2 and R_3.

One benchmark was available for this data set, which allowed comparisons to be made as to the effectiveness and computational efficiency of the proposed SA and TS procedures. This benchmark was the actual operating schedule given in Dare (1994). This schedule, with a cost of 2264 minutes was manually generated using intuition and experience on a day-to-day basis. At the end of one working day, a schedule for the following day was created. The cost of the observed schedule was adjusted to be used as an initial schedule with cost of 1405 minutes for both GPS-SA and GPS-TS techniques. The reasons for adjusting the observed cost schedule are to suit the heuristic and GPS requirements. The original costs were based upon actual travel times between points. However, some of these travel times included long breaks due to the excessive heat: these costs were adjusted to exclude the

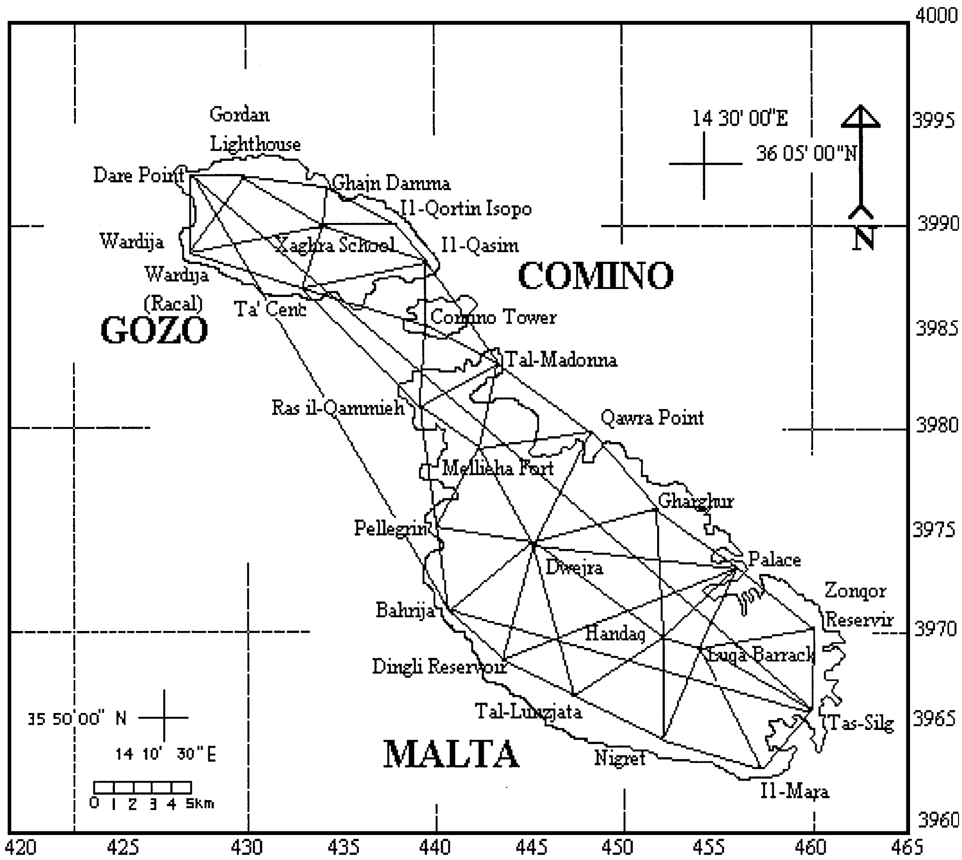


Figure 6. Malta GPS survey network (from Dare, 1994).

stops by simple subtraction. Without this subtraction, some cheap session changes would be excluded from the solution due to the apparently high cost. A further adjustment was made according to the GPS requirement to differentiate between sessions with two receivers and sessions with three receivers. They were arranged into sub-schedules. Thus effectively, the sessions have been partitioned into two distinct types.

The GPS-SA technique using the initial schedule $V_{\text{INT}} = 1405$ minutes was reduced to 1325 minutes (Saleh and Dare, 1998b). Figure 7 shows a graphical depiction of the rapid convergence of the GPS-SA heuristic for this schedule. Using the same initial schedule the overall cost was reduced to 1075 minutes by implementing the GPS-TS technique as shown graphically in figure 8 (Saleh and Dare, 1998d). The behaviour of the developed techniques has been investigated with the variation of their controlled parameters shown in Table 1.

The main goal of the GPS-heuristic techniques is to minimise the overall observation time of the network. The most useful measure for the evaluation of these techniques is the Relative Reduction of the Makespan (RRM) provided by this technique with respect to the

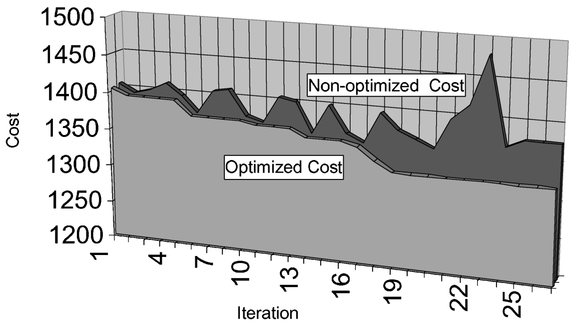


Figure 7. Current and best-found solution quality versus iteration number for the SA heuristic, as it visits five local optima.

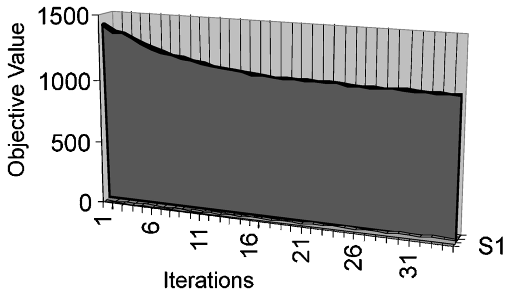


Figure 8. The garph of objective function value versus iteration number for the TS heuristic.

V_{INT}, i.e.,

$$\mathrm{RRM}\% = [(M_{\mathrm{INT}} - M_{\mathrm{BFS}})/M_{\mathrm{BFS}}] * 100.$$

where

RRM = The Relative Reduction of the Makespan.
M_{INT} = The Makespan of the Initial Schedule V_{INT}.
M_{BFS} = The Makespan of the Best Found Schedule V_{BFS} by GPS-heuristic techniques.

Table 1. The controlled parameters of the developed GPS-heuristic techniques applied to the Malta GPS network.

GPS-SA Technique	GPS-TS Technique
Initial temperature T: 75	Tabu list TL: 38*38
Temperature decrement factor F: 0.85	Tabu tenure TT: 3
Markov chain length L: 300	Candidate length CL: 10
Number of iteration K: 14880	Number of iteration KK: 28

Table 2. Summary of the computational results for GPS-heuristics techniques implemented for Malta GPS network.

Technique	V_{INT}	V_{BFS}	RRM%	K	ET
GPS-SA	1405	1325	6	14880	425
GPS-TS	1405	1075	31	28	6

V_{INT}: initial schedule; V_{BFS}: best found schedule; K: number of iterations; ET: execution time (seconds); RRM: relative reduction in makespan.

Considering the observed results using RRM as shown in Table 2, GPS-TS technique clearly outperforms GPS-SA technique with respect to the quality of Best Found Schedule V_{BFS} and computational times. Referring to the V_{BFS}, the average deviation from the V_{INT} shows differences worth noting. The GPS-TS technique obtains much better results, i.e., shorter computation times while increasing the RRM from 6 to 31% as shown graphically in figure 9. The execution time for the GPS-heuristic techniques depends mainly on the total number of iterations. The execution times were about 425 s for 14880 iterations in the GPS-SA down to about 6 s for 28 iterations in the GPS-TS. Since the calculation process is much easier in the GPS-TS technique rather than the GPS-SA technique (no probabilities, no exponential function, no random decisions etc.), this is exactly what one would expect. On the other hand, GPS-TS was able to obtain good schedules with excellent cost value and can be executed from any starting schedule (feasible or not), unlike in the GPS-SA technique where starting with a feasible schedule is important. In this research, all computation times have been measured on a PC (133/MHz) using Visual C++.

A close look at Tables 1 and 2 shows that for reasonable tabu parameters a good schedule can be achieved within a very few seconds. Also, it is possible to obtain a very high quality schedule very quickly. The GPS-TS technique uses a static fixed TL and fixing its parameters a priori seems to be more robust with respect to the schedule quality and computational effort than the GPS-SA technique. For the GPS-SA technique, the choice of the cooling parameters greatly influences the schedule quality. By contrast, the GPS-TS technique in its basic tabu strategy does not require such sensitive parameters. The main reason for this highly quality performance of the GPS-TS technique is due to its search strategy. The use of

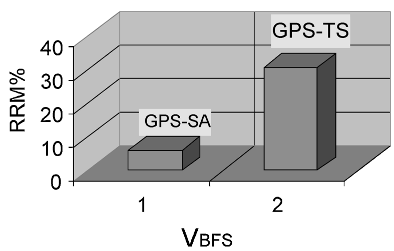


Figure 9. The relative reduction in the makespan versus the V_{BFS} obtained by the developed techniques.

CL strategies offers new ways to avoid extensive computational effort without sacrificing schedule quality. This makes it possible to solve optimally, or close to optimally, large networks on personal computers in few seconds.

In this paper, common forms of memory used in TS (recency-based and frequency-based memories) were implemented. For example, a strict diversification approach keeps track of attribute frequencies over all solutions visited during the history of the search (or of the search within a given region). Then diversification is initiated by seeking to discourage moves to solutions that embody higher frequency attributes or to encourage moves to solutions that embody lower frequency attributes. A strict intensification approach instead keeps track of frequencies over sets of elite solutions (which may be differentiated by clustering). During an intensification phase, high frequency attributes from an elite domain

Recency-Based Memory

=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	=	4	0	0	0	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	=	8	7	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	=	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2	11	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	=	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	=	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	=	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	=	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0
1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=

Frequency-Based Memory

Figure 10. The tabu matrix.

are encouraged or even “locked in”. Ideally, intensification and diversification should not be independent, but allowed to interact, so that each makes reference to the relevant influences from the other. Since TS always has acceptable moves which it can make, even when it is at a local optimum, it is never trapped (Glover et al., 1993). Figure 10 shows the data structure of the length tabu-size. This list is constructed and updated after each iteration. At the beginning the tabu list is empty, then constructed in tabu-size consecutive iterations and updated circularly in later iterations.

From the above discussion and compared with SA, TS is distinct in its use of adaptive memory, with associated short-term and long-term strategies for exploiting such memory. A primary form of short-term memory, on which we have relied in this study, maintains a list of solution attributes to prevent the search from being trapped in local minimum. The tabu list also serves the function of imparting a “heuristic vigor” to the search. From the summary of the computational results, as shown in Table 2, it is concluded that the GPS-TS is preferable to GPS-SA technique in giving a schedule with minimum cost in less computer time for several reasons. First, its flexibility in implementation. Second, the number of iterations done by a search may be fixed a posteriori, unlike GPS-SA technique where starting with a feasible schedule is important.

6. Conclusion

In this paper, a review of the GPS network data in Malta, theory, applications and investigated performance of the developed heuristics are presented. The implementation of the GPS-TS technique with a specific static TL management has been shown to be superior to an implementation of the GPS-SA technique for the Malta GPS network. An apparent advantage of the GPS-TS technique is its greater simplicity. It is not necessary to compute probabilities or to make random decisions. Moreover, GPS-TS yields better results than GPS-SA in a smaller amount of computational time and with a simpler procedure. In the GPS-SA technique it is very important to provide good and carefully chosen annealing parameters, while the GPS-TS technique is rather insensitive in choosing the tabu parameters and the easiest to implement. The GPS-heuristic programs, having been tested on a network for Malta, have provided a detailed understanding of the developed techniques and makes them easily applicable to design any size and different types of networks.

In this research, designing the schedule for a GPS surveying network using heuristics is the first attempt that has been carried out within the GPS surveying and OR literature. This invites other researchers to tackle GPS network surveying with different views and ideas to evaluate its results and heuristics usability. For future work, the development of evolutionary methods such as Genetic Algorithms (GAs) is another crucial direction. This would be another heuristic for solving the GPS logistics problem, then hopefully to provide a third technique to compare and access deviations from optimality.

Another proposed applications of considerable research interest in which heuristic techniques are applicable is to optimize the ambiguity resolution in the GPS data. Resolving the double difference carrier phase ambiguities is the key to precise positioning. The ambiguity inherent with phase measurement depends upon both the receiver and the satellite. A very good result is expected by applying the heuristic technique using the strategic oscillation to locate a high quality and feasible solution to resolve the ambiguity (Kelly et al., 1993) and (Dammeyer and Voss, 1993). The dynamic nature of the heuristic techniques such as in the TS suits the nature of resolving the ambiguity in real time.

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References

Aarts, E. and P. Van Laarhoven. (1985). "Statistical Cooling: A General Approach to Combinatorial Optimization Problems." *Philips Journal of Research* 40, 193–226.

Cerny, V. (1985). "A Thermodynamical Approach to the Travelling Salesman Problem: An Efficient Simulated Annealing Algorithm." *Journal of Optimization Theory and Applications* 45, 41–51.

Dammeyer, F. and S. Voss. (1993). "Dynamic Tabu List Management Using the Reverse Elimination Method." *Annals of Operations Research* 41, 31–46.

Dare, P.J. (1994). "Project Malta' 93: The Establishment of a New Primary Network for the Republic of Malta by Use of the Global Positioning System." Report for Mapping Unit, Planning Directorate, Floriana, Malta.

Dare, P.J. (1995). "Optimal Design of GPS Networks: Operational Procedures." Ph.D. Thesis, School of Surveying, University of East London, UK.

Dare, P. and H. Saleh. (1998). "The Use of Heuristics in the Design of GPS Networks." In F. Brunner (ed.), *Advances in Positioning and Reference Frames*, Proceedings of the Scientific Assembly of the International Association of Geodesy, Rio de Janeiro, Brazil, September 8, 1997. New York: Springer Verlag, pp. 120–124.

De Werra, D. and A. Hertz. (1989). *TS Techniques: A Tutorial and an Application to Neural Networks*, OR Spektrum, Vol. 11. Berlin: Springer-Verlag, pp. 131–141.

Dowsland, K. (1995). "Variants of Simulated Annealing for Practical Problem Solving." In V. Rayward-Smith (ed.), *Applications of Modern Heuristic Methods.* Henley-on-Thames: Alfred Waller Ltd., in association with UNICOM.

Elliott, D. (1996). *Understanding GPS: Principles & Applications*. Boston; Artech House.

Glover, F. (1989). "Tabu Search Part I." *ORAS J. Comput.* 1(3), 190–206.

Glover, F. (1990). "Tabu Search Part II." *ORAS J. Comput.* 2(1), 4–32.

Glover, F. (1995). "Tabu Search Fundamentals and Uses." Technical Report, Graduate School of Business, University of Colorado, Boulder.

Glover, F. and M. Laguna. (1997). Tabu Search. Norwell, MA: Kluwer Academic Publishers.

Glover, F., E. Taillard, and D. de Werra. (1993). "A Users Guide to Tabu Search." *Annals of Operations Research* 41, 3–28.

Hertz, A. and D. De Werra. (1990). "The Tabu Search Meta-heuristic: How We Used It." *Annals of Mathematics and Artificial Intelligence* 1, 111–121.

Kelly, J., B. Golden, and A. Assad. (1993). "Large-Scale Controlled Rounding using TS with Strategic Oscillation." *Annals of OR* 41, 69–84.

Kirkpatrick, S., C.D. Gelatt, and P.M. Vecchi. (1983). “Optimization by Simulated Annealing.” *Science* 220, 671–680.

Leick, A. (1995). *GPS Satellite Surveying*, 2nd ed. Chichester. England: Wiley.

Lin, S. (1965). “Computer Solutions of the Travelling Salesman Problem.” *Bell System Technical Journal* 44, 2245–2269.

Osman, I.H. (1993). “Metastrategy Simulated Annealing and Tabu Search Algorithm for the Vehicle Routing Problem.” *Annals of OR* 41, 421–451.

Osman, I.H. and C.N. Potts. (1989). “Simulated Annealing for Permutation Flow-Shop Scheduling.” *Omega* 17, 551–557.

Reeves, C.R. (ed.). (1993). *Modern Heuristic Techniques for Combinatorial Problems*. Oxford, England: Blackwell Scientific Publications.

Rene, V.V. Vidal. (1993). *Applied Simulated Annealing*. Berlin: Springer-Verlag.

Saleh, H.A. (1996). “Improvements to The GPSdemoUCL Simulation Software.” MSc. Dissertation in Surveying, Department of Geomatic Engineering, University College London, London, UK.

Saleh, H.A. and P.J. Dare. (1997a). “A Heuristic Approach to the Design of GPS Networks.” Paper presented at Untied Kingdom Geophysical Assembly-21, University of Southampton, UK, 2–4 April 1997.

Saleh, H.A. and P.J. Dare. (1997b). “The Design of GPS Networks using the Heuristic Techniques.” Paper presented at Young Researchers Forum in Operational Research and Management Science, University of Southampton, UK, and 17–18 April 1997.

Saleh, H.A. and P.J. Dare. (1997c). “A Simulated Annealing Approach for Designing a GPS surveying Network.” Paper presented at 2nd Meta-Heuristic International Conference (MIC’97), Sophia-Antipolis, France, 21–24 July 1997.

Saleh, H.A. and P.J. Dare. (1998a). “Efficient Simulated Annealing Heuristic Techniques for Designing GPS Surveying Networks.” Paper presented at Young OR10 Conference, University of Surrey, Guildford, UK, 31 March to 2 April 1998.

Saleh, H.A. and P.J. Dare. (1998b). “GPS Network Design An Application of The Simulated Annealing Heuristic Technique.” Paper presented at International Conference on Combinatorial and Global Optimization, Chania, Crete, Greece, 25–29, May 1998.

Saleh, H.A. and P.J. Dare. (1998c). “Heuristic Techniques for GPS Surveying.” Paper presented at UEL Postgraduate Conference, University of East London, Startford, UK, 5 June 1998.

Saleh, H.A. and P.J. Dare. (1998d). “A Tabu Search Approach for Designing a GPS Surveying Network for the Republic of Malta.” Paper presented at 16th European Conference on Operational Research, Brussels, Belguim, 12–15 July 1998.

Taillard, E. (1994). “Parallel Taboo Search Techniques for the Job Shop Scheduling Problem.” *ORSA, Journal on Computing* 6, 108–117.

Teunissen, P. and A. Kleusberg. (1998). *GPS for Geodesy*, 2nd ed. Berlin: Springer-Verlag.