HEURISTICS FOR IMPROVED EFFICIENCY IN THE USE OF THE GLOBAL NAVIGATION SATELLITE SYSTEMS FOR ESTABLISHING POSITIONING NETWORKS

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Abstract

Global Navigation Satellite Systems (GNSS) are becoming increasingly crucial in the practice of geomatics and earth sciences. When related to positioning (through a network of points visited a number of times by relevant receiving equipment) the use of GNSS techniques is highly expensive and the management costs grow exponentially as the number of relevant parameters increases. These parameters include time, sessions to be observed, receivers and satellites to be used, stations to be co-ordinated, vehicles, personal availability. The problem is to model the above parameters in order to optimize the network design within economical as well as geometric constraints. The complexity of designing positioning networks using satellite technology increases with their size. Large networks become highly difficult to solve effectively using exact methods. Heuristic techniques, which are often based upon ideas from Artificial Intelligence (AI), have been implemented to efficiently provide flexible and computerized procedures for solving this problem.

Key words: Global Navigation Satellite System (GNSS), Heuristics, Network, Operational Research

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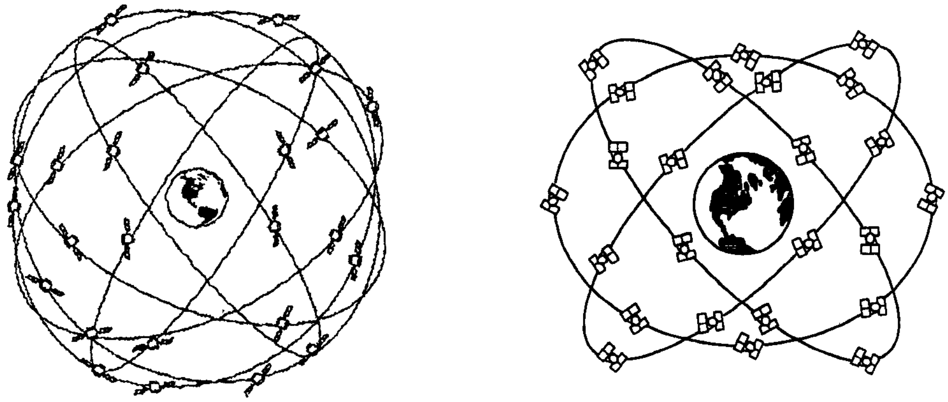


GPS GLONASS

Figure 1. The GPS and GLONASS constellation of navigation satellites [1]

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have revolutionised positioning, navigation, and timing in the last decade. They have changed the way people navigate the oceans, the air and land, as well as touching our lives in many other ways, from agriculture, to engineering and architecture. GNSS are space-based satellites systems used to determine positions on and above the earth and its oceans using suitable satellite receiving equipment. The receivers on the earth can calculate their positions with great precision by determining their distance from four or more satellites. The Global Positioning System (GPS) and the GLObal NAvigation Satellite System (GLONASS) are the most widely known satellite navigation systems. These systems are being developed by the USA and Russia respectively (see Figure 1). These systems have much in common in terms of the satellite constellation, orbits, signal structure, etc. On the other hand, both systems are autonomous, each with their own time reference and spatial co-ordinate system. The GPS and the GLONASS operational constellations nominally consist of 24 satellites orbiting the earth. They provide the user with a 24-hour highly accurate three-dimensional position, velocity and timing system at almost any global location [2, 3].

Both systems provide a similar level of service and their integrated use potentially offers scientists many advantages. Integrated use of GPS and GLONASS constellations can be achieved by combining measurements from the two systems and overcoming some technical and quality issues that needs to be addressed.

The advantages of integration include coverage, accuracy and integrity monitoring. One of the examples of the main benefits to scientists will be the increase in coverage, making it possible to determine positions in locations that would otherwise be obstructed. For geodetic, surveying and navigation purposes, networks observed by GNSS techniques are covering large extents of the Earth's surface. Table 1 summarises the salient features of the GPS and GLONASS constellations. In this research, it is the use of GPS to establish positioning networks that is being investigated.

System	GPS (American)	GLONASS (Russian)
Constellation		
Number of satellite	24	24
Number of orbital planes	6	3
Orbital inclination (deg)	55	65.8
Orbital radius (km)	26,560	25,510
Period (hr:min)	11:58	11:16
Ground track repeat	sidereal day	8 sidereal days
Signal Characteristics		
Carrier signal (MHz)	L1:1575.42 L2:1227.60	L1:(1602+0.5625n), L2:(1246+0.4375n), $n=1,2,.....,24$
Code	CDMA C/A code on L1 P code on L1 and L2	FDMA C/A code on L1 P code on L1 and L2
Code frequency (MHz)	C/A code:1.023 P code:10.23	C/A code: 0.511 P code: 5.11
Reference standards		
Coordinate System	WGS84	PZ90
Time	UTC(USNO)	UTC(SU)
Accuracy specification (95%)		
Horizontal (m)	10	100
Vertical (m)	15	250

Table 1. Characteristic of GPS and GLONASS Systems [1]

Compared to other positioning techniques, satellite techniques provide unprecedented positioning accuracy for the ground based receivers. On the other hand, using these space-based satellite techniques is highly expensive and this cost becomes crucial as the amount of fieldwork increases for large networks. GNSS positioning fieldwork consists of controllable and uncontrollable variables such as time, cost, personnel, location of stations, receivers and satellites to be used, and sessions to be observed. A receiver is a device that can receive a radio signal from a satellite to provide information on the location of the device. In surveying (at least two receivers) are placed at key locations and take simultaneous measurements from a number of satellites. The receivers are then moved to other locations for further measurements. The purpose is to obtain highly; accurate measurements which can be used to define the positions of the receiver locations relative to each other.

The main purpose of this research is to model the components of the GNSS positioning fieldwork using heuristic techniques, within the field of Operational Research (OR), in order to determine the best logistics design based on geometrical and cost restrictions. The GNSS positioning network within the frame of heuristics will be formulated. The heuristic strategy search will be introduced and the elements of the methodology of the developed techniques will be defined. Testing of these techniques on hypothetical and real networks of different types and sizes will be described. Finally, the performance of the developed techniques based on computational effort and solution quality will be reported. Conclusions and directions for future work will be given.

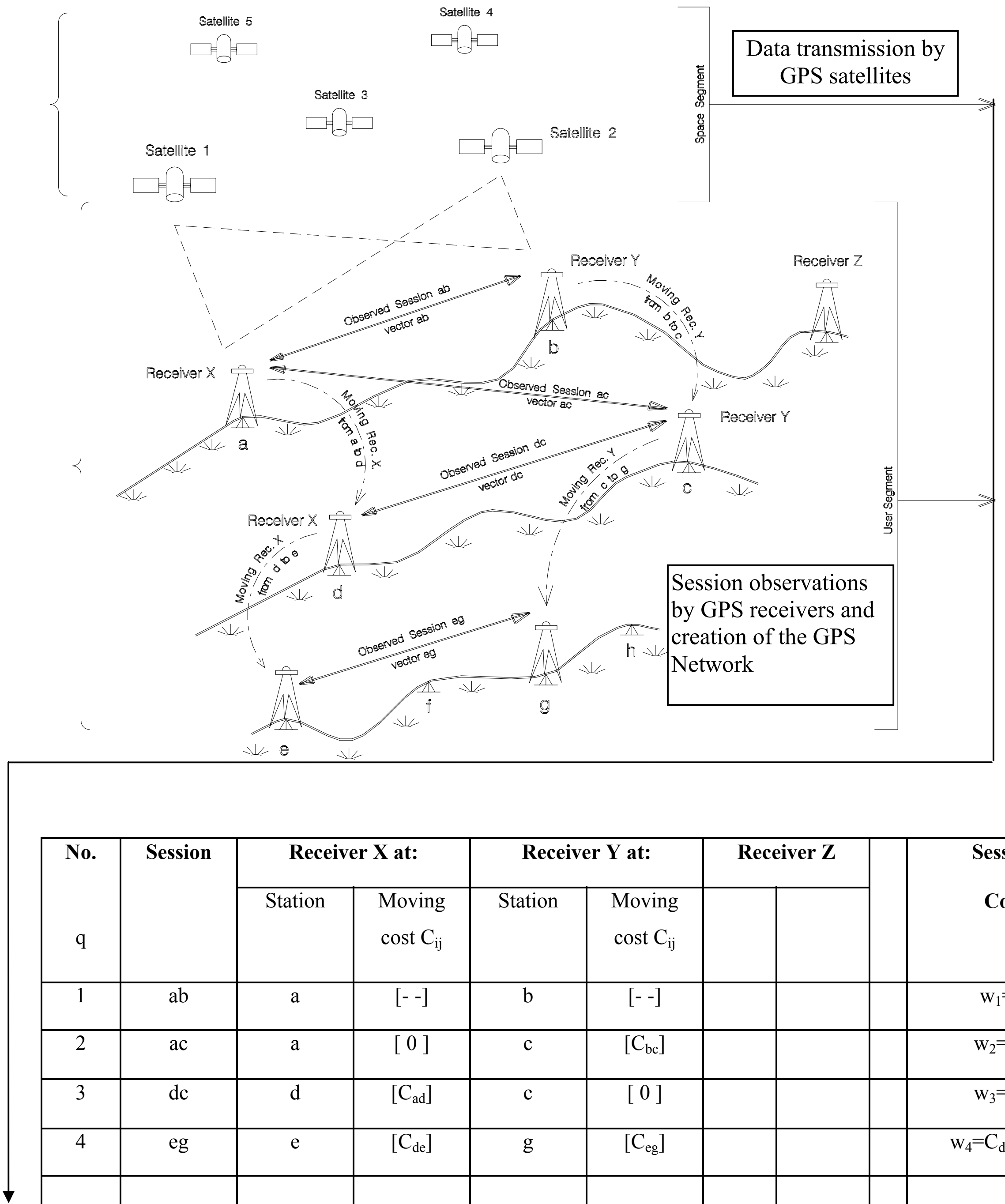
2. THE SATELLITE POSITIONING NETWORK PROBLEM

Previously it was terrestrial networks (i.e., networks not based on use of satellite techniques) that formed the foundation of most geomatics activities. Their design, which was the basic framework for geomatics information in many countries, was based on intuition and empirical formulae [4]. Later, a computer simulation technique was developed in order to test networks prior to any observations being made [5].

More recently, establishing control has become dominated by satellite techniques [6]. GNSS has the ability to perform precise positioning for geodetic and surveying purposes in a fraction of the time and cost than required by terrestrial methods. However, this achievable precision for large networks can be optimized if the GNSS logistics of the fieldwork can be investigated. GNSS logistic was thoroughly explained in Dare [7], but a brief summary of the logistics of GNSS fieldwork is illustrated in Figure 2. Figure 3 shows the simplified functional flow chart diagram for designing a positioning network based on the logistics of the GNSS fieldwork. When related to satellite technology, a positioning network can be defined as a number of stations (a, b, c, etc) which are co-ordinated by placing receivers (X, Y, Z, etc) on them for a number of sessions (ab, ac, etc), as shown in Figure 2. In this figure, the notation C_{ij} represents the cost of moving a receiver from station i to station j. A session can be defined as a period of time during which two or more receivers simultaneously record satellite signals. At least one receiver is then moved to a new station and a new session commences. The schedule of receivers can be defined as a sequence of sessions to be observed consecutively. For this application, the aim is to search for the best order in which these sessions can be organized to give the schedule with minimal cost using an acceptable amount of computational effort [8].

The development of computationally efficient techniques that can satisfy the requirements of specific aspects of GNSS positioning (e.g., logistics) are lagging behind the developments in GNSS technology. Therefore, the need for efficient computerized scheduling procedure in GNSS positioning is extremely necessary. There are difficulties in the design of GNSS positioning networks that relate to the establishment of good schedules. Currently, an experienced surveyor creates the schedule manually using intuition and experience. A first attempt to optimize the design of a GNSS positioning network problem within the OR field was based on a transformation of the problem into a Travelling Salesman Problem (TSP) [9].

However, this exact method is limited to relatively small networks. Given N stations and R receivers, the number of the sessions S could be as large as N!/(N-R)! and the problem would become too difficult to solve using exact methods. As a consequence, the development of effective computer based heuristic techniques for the above mentioned problem have been designed and analyzed theoretically and empirically. These techniques allow the formulation of a strategy for designing satellite positioning networks which maximise the satellite technology benefit by reducing the total cost of carrying out the survey. Within the GNSS positioning and OR literature, applying heuristic techniques to design large GNSS networks represents a new area of research [10].



No.	Session	Receiver X at:		Receiver Y at:		Receiver Z			Session
q		Station	Moving cost C_{ij}	Station	Moving cost C_{ij}				Cost
1	ab	a	[- -]	b	[- -]				$w_1 = 0$
2	ac	a	[0]	c	$[C_{bc}]$				$w_2 = C_{bc}$
3	dc	d	$[C_{ad}]$	c	[0]				$w_3 = C_{ad}$
4	eg	e	$[C_{de}]$	g	$[C_{eg}]$				$w_4 = C_{de} + C_{eg}$
The total cost of the schedule									$\sum_{q=1} w_q$

Figure 2. Observation of sessions using GPS receivers.

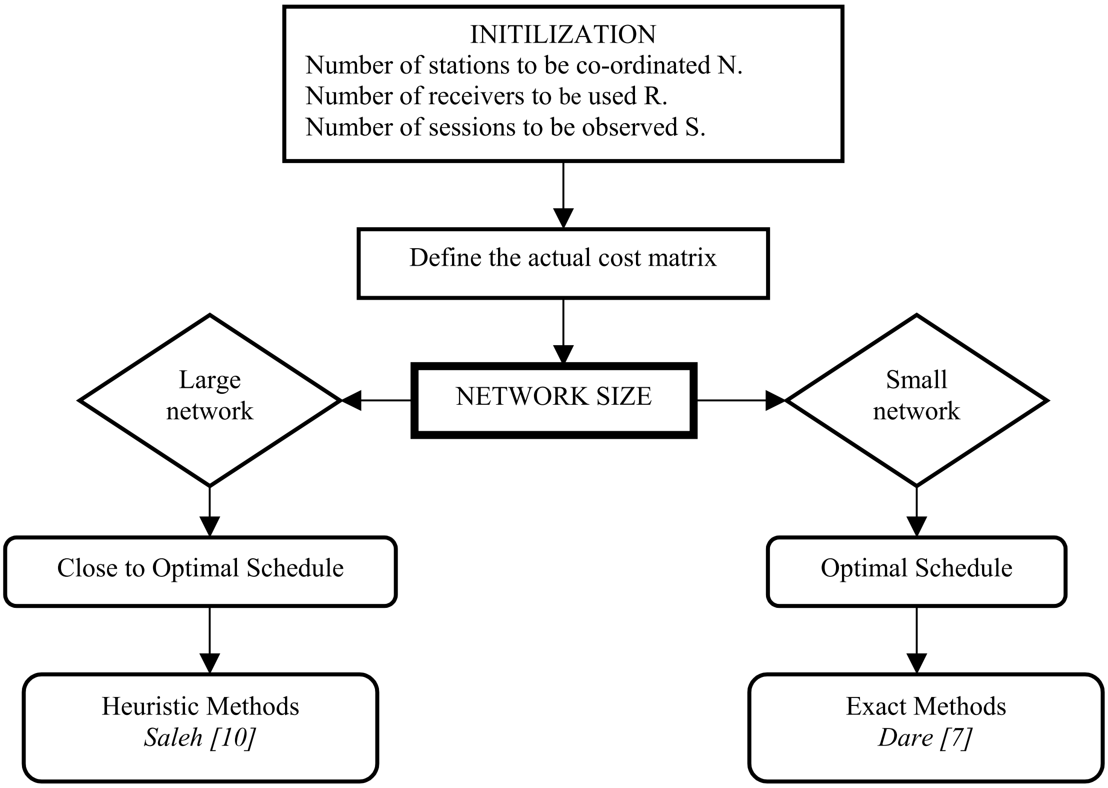


Figure 3. Simplified functional flow chart diagram for designing a positioning network based on logistics of the GNSS fieldwork.

3. HEURISTIC TECHNIQUES FOR SATELLITE POSITIONING NETWORKS

Experimental results show that heuristic techniques have proved useful for a wide range of complex real-life problems related to management science, engineering and computing science [11, 12, 13]. A heuristic technique starts with an initial solution (within this context, an initial schedule). It iteratively attempts to improve upon the current solution by a series of improving changes generated by a suitably defined neighbourhood mechanism until a stopping criterion is met. A neighbourhood of a solution (V) is a set of solutions (V_1, V_2, V_3,...,V_n) that can be reached from (V) by a simple operation such as removing or adding an element (within this context, a session) to (V). The fundamental concepts of any heuristic technique consist of: representation and construction of the initial solution; generation of neighbouring solutions; acceptance strategy; and stopping criteria. The heuristics that have been implemented in this research are Simulated Annealing (SA) and Tabu Search (TS). The SA technique derives from physical science, whereas the TS technique stems from general tenets of artificial intelligence problem solving. On the other hand, both SA and TS techniques combine different operational and organizational strategies based on robustness and computer models in order to obtain high-quality solutions [14].

3.1 Simulated Annealing (SA)

The SA technique is a stochastic search procedure inspired by the annealing of metals [15]. This technique always accepts good changes but bad changes are treated with non-zero probability. Specifically, in each iteration, this technique generates a set of neighbours of the current schedule; if a neighbour has lower cost, then the technique moves to it, otherwise it moves to another neighbour with a probability P (Δ, T). This probability depends on the cost differential Δ and on an adjustable temperature T. During the course of the cooling process, the temperature is adjusted starting from a high value (which yields a higher probability P of an uphill move) but tends towards zero as the number of iterations increases. At high temperature, the search is almost random, while at low temperature the search becomes almost ‘greedy’, i.e., only a good solution is accepted. Figure 4 shows the functional flow chart diagram for the implementation of the SA technique for GNSS positioning.

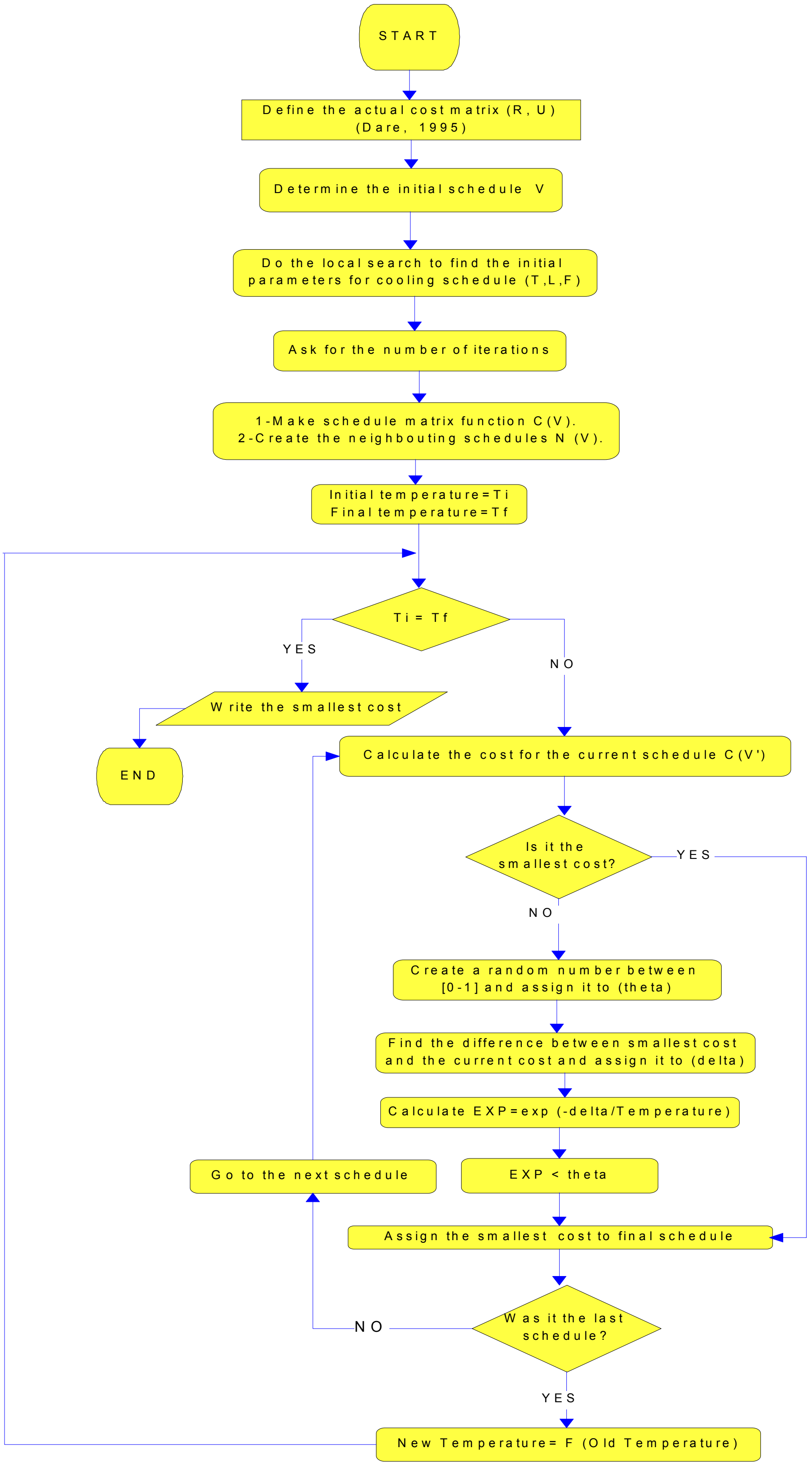


Figure 4. Functional flow chart diagram for the SA technique.

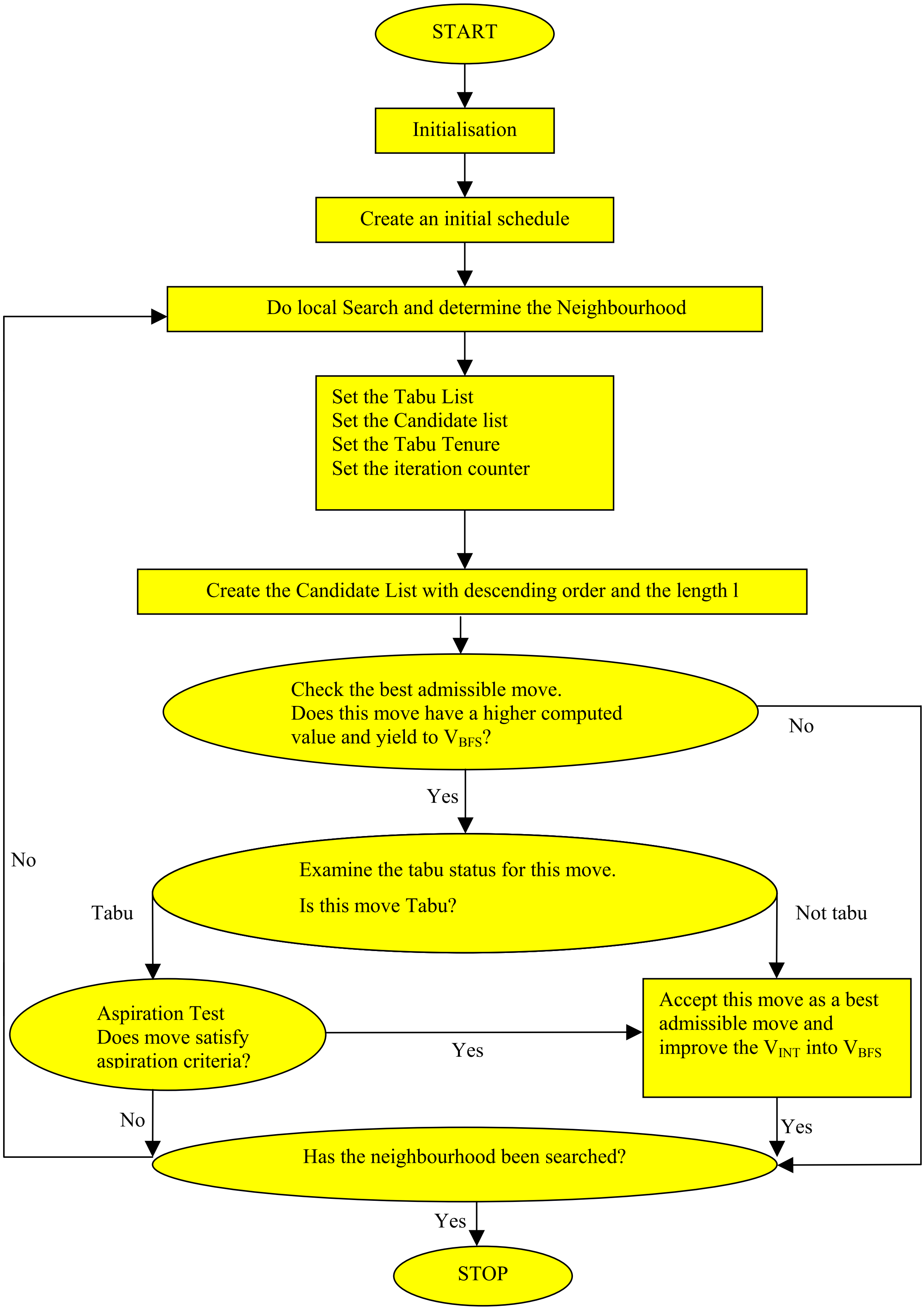


Figure 5. The functional flow chart diagram for designing the TS technique.

3.2 Tabu Search (TS)

The TS technique is an aggressive search technique based on the systematic exploration of memory structures [16]. This technique generates several neighbouring solutions and selects the best solution among all current candidate solutions. In order to avoid 'cycling', the move that reverts to the more expensive schedule just visited is prohibited. This forbidden task is accomplished by keeping the prohibited move tabu in a matrix structure called the Tabu List. The TS technique, using this candidate list strategy, offers better ways to save computational effort without affecting schedule quality. The length of this list is a trade-off between quality and computation effort. Figure 5 shows the functional flow chart diagram for the implementation of the TS technique for GNSS positioning.

4. COMPUTATIONAL EXPERIENCE

The effectiveness of a heuristic technique can be measured by comparing its performance with an optimal schedule with reference to the solution quality and computational effort. Fortunately, there are such known optimal schedules based up on exact methods for relatively small GNSS positioning networks [7]. The schedules obtained using the SA and TS techniques have the same results as the known optimal schedules [17]. Measuring the performance evaluation of heuristics on large networks for which the optimal schedules are not known may be quite difficult [18]. The criterion adopted in this research is to apply the different heuristic techniques on large networks and then to compare their computed schedules. Two large networks of different type and size in Malta and the Seychelles were used. The triangular-type network of the Republic of Malta consists of 25 stations [19]. The initial schedule with a cost of 1405 minutes was composed of 38 sessions, each of which used either 2 or 3 receivers. The linear-type network of the Republic of Seychelles consists of the 75 stations [20]. The initial schedule with a cost of 994 minutes consisted of 71 sessions, each of which used three receivers.

The performance of the heuristic techniques is evaluated through the Relative Reduction of the Cost (RRC) provided by these techniques with respect to the initial schedule, i.e., RRC= $[(V_{INT} - V_{BFS})/ V_{INT}]*100$.

where

S : Number of sessions.

V_{INT} : Initial schedule.

V_{BFS} : Best Found Schedule by the heuristic technique.

ET : Execution Time in seconds.

Network Information			**Heuristic Techniques**					
			SA			**TS**		
Network	S	V_{INT} (mins)	V_{BFS} (mins)	RRC%	ET (sces)	V_{BFS} (mins)	RRC%	ET (secs)
Malta	38	1405	1355	3.56	425	1075	23.49	6
Seychelles	71	994	976	1.81	1700	933	6.14	40

Table 2. Comparison of heuristic techniques applied to different types of networks.

Analysing the results in Table 2 with respect to the Malta network, the RRC of the V_{BFS} of the SA technique was 3.56% obtained by 14880 iterations with a computation time of 425 seconds. Compared to the V_{BFS} of the TS technique, an RRC of 23.49% was obtained by 28 iterations with a computation time of 6 seconds. In the Seychelles network, the RRC of the V_{BFS} of the SA technique was 1.81 % obtained by 115920 iterations with a computation time of 1700 seconds. Compared to the V_{BFS} of the TS technique, an RRC of 6.14 % was obtained by 20 iterations with a computation time of 40 seconds. The above results indicate that the TS technique consistently produced better schedules. It is clear that the calculation process is much easier with the TS technique compared with the SA technique (i.e. there are no probabilities, no exponential functions, no random decisions etc). The TS technique concentrates its search efforts on the best of the candidate schedules. In contrast, the SA technique spends most of its time evaluating poor quality schedules. This phenomenon is in agreement with the literature [21, 22, 23].

For both networks, the developed heuristic techniques yielded good schedules. The best results are obtained for the triangular-type networks. It is clear that, because of the larger number of available states for each move, the ability of the developed heuristic techniques to obtain an improved schedule for the triangular-type networks will be greater than the linear-type networks as shown in Figure 6 and Figure 7. This is partly because for a linear-type network, the initial schedule is likely to be closer to the optimal schedule due to the limited number of reasonable choices of schedules. Thus, a better heuristic schedule for GNSS positioning networks can be produced for triangular-type networks because of the larger number of reasonable choices available for each schedule. The heuristic techniques have been coded in the visual C++ programming language.

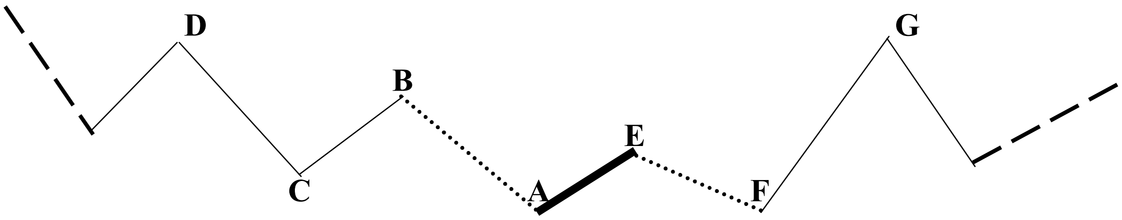


Figure 6. Linear-type network.

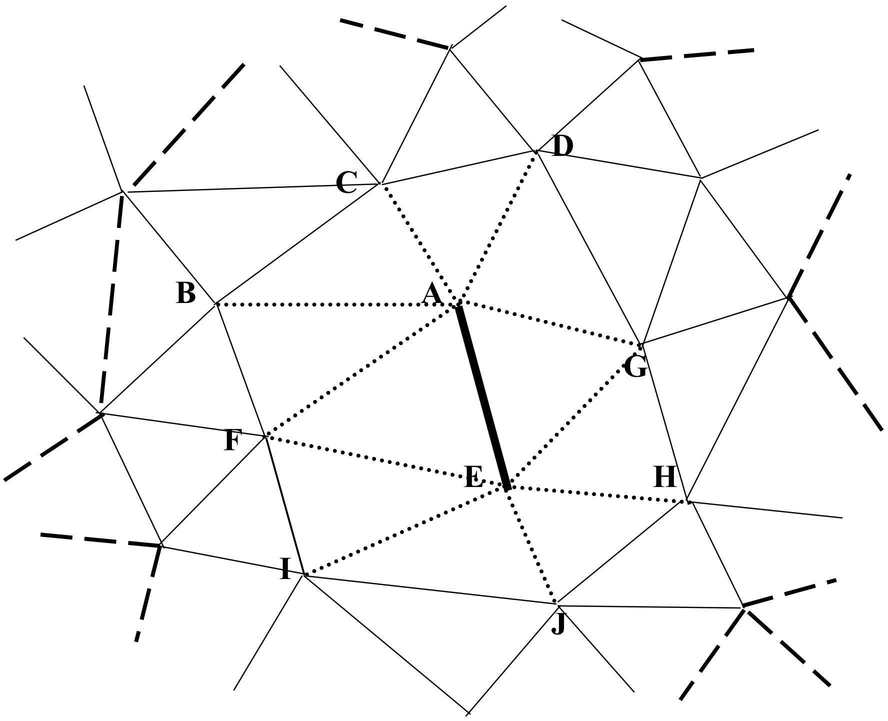


Figure 7. Triangular-type network.

where the lines used in the above figures represent the following status:

▬▬▬▬ Current session i.

······················ Reasonable session i+1.

— — — — Unreasonable session i+1.

5. CONCLUSIONS

Efficient use of heuristic techniques is a creative process and depends on the skill and experience of the surveyor, size and type of a network and the empirical analysis. The encouraging results presented in this paper have provided motivation and useful insights for undertaking additional research. The main aim of this research is to develop further heuristic techniques and search for a better way of finding good solutions quickly [24]. Initial investigation with other heuristic techniques such as genetic algorithms and ant colony optimization algorithms on similar applications to the GNSS positioning problem indicate that there is still much potential for improvement. Genetic Algorithms (GAs) are inspired by biological sciences and have proved to be an effective optimization technique [25]. Ant Colony Optimization (ACO) algorithms are another nature-inspired heuristic introduced by Dorigo and colleagues [26, 27]. The basic idea underlying ACO is that of simulating the behaviour of a set of agents that co-operate to solve an optimization problem by means of very simple communication. Preliminary results suggest that these heuristics could be applied successfully to the GNSS positioning problem. This provides strong motivation and a fertile opportunity for innovation in adapting heuristics for solving other practical geomatics optimization problems where feasibility and good solutions are difficult to obtain [28].

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