THE JOURNAL OF NAVIGATION (2003), **56**, 123–136. © The Royal Institute of Navigation
DOI: 10.1017/S0373463302002047 Printed in the United Kingdom

Telemetric Control of Remote Vehicles using an Inverse RTK Technique

Ahmed El-Mowafy

(*The United Arab Emirates University*)

In this study, an inverse Real Time Kinematic (RTK) GPS positioning approach is presented and discussed. GPS data from a remote receiver mounted on an unmanned vehicle is sent to the base station to determine the vehicle location at the centimetre level of accuracy in real time. Control of the vehicle's movement and manoeuvring can thus take place at the base station, which could be a few kilometres away, and the vehicle can be sent to specific locations to do certain tasks. Two GPS antennas were used in order to increase positioning reliability and estimate real time heading and pitch of the vehicle for better control. In addition, the vehicle was fitted with cameras with wireless video transmission to provide the operator with a good level of vision in different directions during operation. The main applications of such a system would be in exploration, breaching and clearance of minefields, and hazardous situations such as fire fighting of burning oil wells. The system design and techniques employed are discussed first. Issues addressed include antenna layout, data transmission, solution algorithm, and ambiguity resolution. The proposed system was mounted on a prototype vehicle and tested under different satellite visibility conditions. Results show that high positioning accuracy with reliable ambiguity resolution can be obtained with the developed approach if the number of observed satellites is 5 or more and PDOP is less than 5. Heading and pitch were determined within 0·2–0·3 degree using a 1·2 m long baseline. This performance can be improved as the length of the on-board baseline increases.

KEY WORDS

1. GPS. 2. Vehicle Navigation. 3. Telematics.

1. INTRODUCTION. In a traditional Real Time Kinematic (RTK) technique, the coordinates of a GPS receiver, mounted on a moving object (rover), are determined by referencing it to a point of known position, where the measurements or their corrections are sent from the reference station (base) to the rover. Thus, positioning is carried out at the rover, while the base does not usually know the rover location. There are, however, applications that require the knowledge of the rover's precise coordinates at the base, for instance, in fleet management and telemetric control of unmanned vehicles that can be used in hazardous or risky missions. To achieve this goal, the RTK traditional method has to be reversed. That is, the rover has to send its data to the base, where estimation of the rover location can be carried out on line. This approach can be defined as the inverse RTK method. The method can be augmented to determine the real-time orientation (attitude) of the rover. In this case, three dual-frequency GPS receivers would be needed, two to be mounted on the rover, and the third receiver to occupy the reference point (base), which also forms the control station for telemetric control of the vehicle. The two

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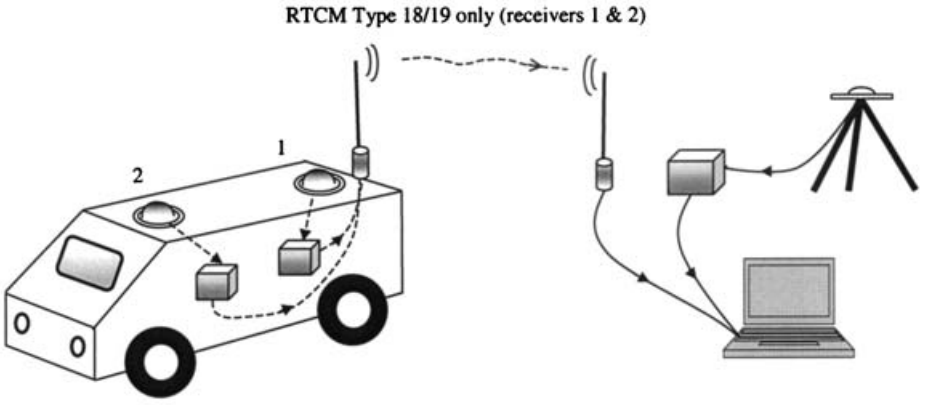


Figure 1. The inverse RTK approach for position and attitude determination.

units are needed on the rover for heading and pitch determination as well as enhancing positioning reliability.

This paper describes the methodology of a developed inverse RTK approach. Its performance in position and attitude determination is tested for relatively short baselines (approximately 4 km). A few details on the components and operation of the telemetric control system as a whole are given.

2. THE INVERSE RTK APPROACH.

2.1. *Data Format*. In the inverse Real Time Kinematic (RTK) GPS positioning approach, GPS data is sent from the remote receiver to the base station, where determination of the rover position will be carried out in real time. In this method, the data sent from the rover to the base will be in the standard RTCM Version 2.1–2.3 format message types 18/19 ('raw' uncorrected carrier phase and pseudo-range measurements). Since position computation is carried out at the base, whose coordinates are well known at the mm level of accuracy, there is no need to use message type 1 (pseudo-range corrections), type 3 (base-station information and coordinates), and type 22 (enhanced base-station accuracy resolution). Therefore, the message size in the inverse RTK is much smaller than in the traditional rover-to-base RTK techniques. In addition, for efficient data transmission and to reduce latency, a binary-compressed form of the data can also be used; however, this does create some limitations on the type of receivers used if implemented commercially.

The same concept can be applied by mounting two receivers onboard the rover vehicle. The two receivers can be used for position and attitude (heading and pitch) determination of the vehicle, which are computed at the base station using the inverse RTK method. Figure 1 illustrates the basic elements of this approach.

When compared with the majority of traditional RTK methods employing the RTCM type 20/21 message (carrier phase and pseudo-range corrections), implementing message type (18/19) in the inverse RTK requires the processing algorithm to account efficiently for any differences in the measurement time between the base station and the rover receivers. This is due to the fact that corrections change slowly with time while the raw measurements change rapidly. Thus, due to latency, a method

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of predicting the phase data at the exact instant of measurement collection at the base is developed, which takes into account the rover dynamics that are modelled based on the expected level of motion. The messages also have to be sent at a faster rate to reduce accuracy degradation due to the prediction process. Thus, a measurement rate of 5–10 Hz is proposed with a datalink of a baud rate 19 200. In addition, delayed accurate positions are computed from measurements referring to the same epoch for the base and rover, and stored and used to refine the prediction algorithm. The uncorrected carrier phase data rollover (occurring when the carrier phase value exceeds 2^{31}) should also be accounted for before processing. On the other hand, the use of message type 18/19 guarantees that the same ephemeris set will be used for both the rover and the base phase measurements (using the ephemeris file at the base). This avoids a possible error in computing the corrections at one point and applying them at another if an ephemeris changeover occurs, and is accounted for in one site but not the other.

2.2. *Operational Issues.* The inverse RTK system operation can be defined according to the type of communication employed between the reference and the user, either as omni-directional or bi-directional (duplex). This is dependent on the nature of the application. In the first type, the rover only sends its phase measurements to the reference as described above, where the rover position is determined at the control station. In telemetric control of vehicles, upon reception of the rover position and video data, telemetric commands can be sent via a datalink to the vehicle to control its motion. In the second case, the duplex mode, the reference station computes the rover positions in an inverse RTK approach and sends them back to the rover together with the measurement corrections, which are computed for the rover location in RTCM message type 20/21 format. The corrections are sent along with the telemetry commands via the datalink and these data are stored in the rover and regularly predicted. The corrections are estimated for both L1 and L2 frequencies. These corrections can be applied to the raw data similar to traditional RTK to aid position estimation needed by an Advanced Driver Assistance Systems (ADAS) in a situation of signals from the reference station being lost for a few seconds. Since the corrections are only needed here as a backup, they can be sent at a slow rate, e.g. every 10 seconds, while the base station coordinates are sent only once using RTCM type 3 and type 22 messages at the beginning of the survey. The measurement corrections can be computed as follows:

$$\delta_\phi = (\mathrm{r} - \mathrm{t_{sv}} \,.\, \mathrm{c} + \mathrm{T_{rov}} \,.\, \mathrm{c})/\lambda - \phi - \mathrm{A}, \tag{1}$$

$$\delta_\rho = (\mathrm{r} - \mathrm{t_{sv}} \,.\, \mathrm{c} + \mathrm{T_{rov}} \,.\, \mathrm{c}) - \rho, \tag{2}$$

where:

δ_ϕ, δ_ρ are the rover carrier phase and pseudo-range measurement corrections, respectively, uploaded in message types 20 and 21.

r is the computed range in metres from the satellite to the estimated position of the rover using the inverse RTK approach.

$\mathrm{t_{sv}}$, $\mathrm{T_{rov}}$ are the satellite clock offset computed from the satellite clock model, and the estimated clock offset of the rover receiver, respectively.

c is the speed of light.

λ is the carrier wave length (L1 or L2).

ϕ is the carrier phase measurements in cycles (L1 or L2).

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A is an arbitrary integer number of cycles (constant) chosen at the start of tracking to keep the size of the corrections small.

ρ is the pseudo-range measurements.

To maximize the area covered by the inverse RTK, the antenna of the reference station should be placed in locations free from the impact of multipath and mounted as high as possible. Naturally, the transmission range (propagation distance) between the rover and the base are dependent on the power of the modem; however, like in traditional RTK, the maximum range (d) when using the inverse RTK employing VHF/UHF frequencies can be approximated by: (Langley, 1998).

$$d = 3{\cdot}57\sqrt{k}(\sqrt{h1} + \sqrt{h2}), \tag{3}$$

where:

h1 & h2 are the antenna heights at the transmitting and receiving receivers; respectively, approximated above average terrain.

k is the effective earth radius factor (varying between 1·2 and 1·6, with a typical value of 1·33).

From equation (3), the maximum range for antennas of 2 m height at the reference and the rover without repeaters will be 11·64 km. However, if a 2-watt amplifier is used, the range is limited to approximately 2 km (based on the author's experience; this can vary dependent on working conditions). In practice, the actual range is thus dependent on the power of the transmitting radio, the interference environment, the terrain geometry, the antenna setup, and the density of structures of the working area. Placement of radio-modem repeaters can thus be critical to successful use of inverse RTK positioning. However, this may result in more data delay and degradation of accuracy. The repeaters can be mobile, mounted on a surveying truck, moving between locations within the site according to progress of the work. In addition, in presence of the two rover receivers and possibly other radios in the work area, it is recommended that each radio is assigned a unique ID (radios should be selected to have such capability), and have a scanning function that the base radio can automatically scan for the best open channel and the rover radio scans for the base transmission.

Once the base and rover measurements have been collected, and/or the corrections have been applied to the raw measurements for each satellite individually at both the reference station and the user, a standard ambiguity resolution method can be applied. Currently there are a number of reliable algorithms that can be utilized for the RTK approach, which can be directly applied for the inverse RTK approach without modifications and give a solution within a few seconds. Kim and Langley (2000) give a summary of the characteristics and methodologies of most of these techniques.

The method used in this research for ambiguity resolution is based on the Least-squares Ambiguity Decorrelation Adjustment (LAMBDA) technique, which was originally developed by Teunissen (1995). The approach taken with the LAMBDA method is to re-parameterize the integer least-squares problem such that an equivalent but easier problem is obtained. The method is an *all ambiguities search* approach, which is carried out in three steps – the float solution, the integer ambiguity estimation, and the fixed solution. Since dual-frequency receivers are used, a wide-lane combination of L1 and L2 is utilized for the ambiguity resolution; afterwards, the resulting position from the wide-lane solution is used directly to compute the L1 ambiguities. Similar to the RTK positioning method, the level of success of the 'On The Fly' (OTF) ambiguity resolution implemented in the inverse RTK is a function of the number and

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geometry of the satellites observed, the quality of measurements, the reference-to-rover distance, and the impact of measurement errors – in particular the ionospheric and signal multipath errors (El-Mowafy, 2000).

Minimising the ionospheric error is usually a primary concern in RTK positioning for determination of correct 'fixed' carrier-phase ambiguities, and improving positioning accuracy as well as reducing latency. If long base-to-rover ranges are needed, more efficient models of the ionospheric error and other spatially correlated errors will be required. A model that estimates the gradient of ionospheric changes from data of multiple reference stations is applied to estimate the ionospheric error at the rover according to the base-to-rover distance. To minimise the tropospheric errors in the proposed inverse RTK method, a modified Hopfield model is used.

One unique error in RTK positioning is data latency. Latency time could range between 0·1 to 1 second or more, depending on the amount of data sent (particularly the number of satellites observed), type of datalink used, reference-to-remote distance, and the measuring conditions. To reduce degradation of accuracy due to latency, a rapid approach is implemented as mentioned above, where a prediction algorithm is applied to estimate the rover measurements from the previously received ones. Some positioning errors at the cm level of accuracy can thus be expected depending on dynamics of the rover's movements.

For longer reference-to-rover distances, the use of the traditional technique that employs one reference station can be replaced by using the concept of a network of reference stations. In this case, any of the reference stations or a station that has access to their data can be used as the base of the inverse RTK approach. It is believed that in the near future, such networks will cover all major cities in the world. In the United Arab Emirates, a regional network covering the Emirate of Dubai started functioning in early 2002; other Emirates will soon follow. The utilization of the regional network of reference stations helps in reducing the processing time to integer ambiguities resolution, increases robustness and reliability, and increases the distance over which the cm level of accuracy can be achieved (Cannon *et al*., 2001). The network stations operate for tens of kilometres in reference-to-rover ranges, which is far more than the typical case, in which the maximum range is 10–15 km using a single reference point. For simplicity, communications between the network stations can be carried out on line on the Internet (Petrovski *et al*., 2000; Hada *et al*., 2000). For more details on the methodologies used in utilization of multiple reference station networks, refer to Fortes *et al*. (1999), Enge *et al*. (2000), Euler *et al*. (2001), and Raquet and Lachapelle (2001).

3. STRUCTURE OF THE TELEMETRIC CONTROL SYSTEM USING THE INVERSE RTK AND VIDEO INPUT.

The design of a system for telemetric control of remote vehicles requires the integration of different types of sensors with wireless communications. The proposed system, mainly consists of:

(a) A telemetry controlled unmanned test vehicle (Figure 2), which is equipped with:
   (i) two dual-frequency GPS units (Ashtech 12-channel receivers) used for position and attitude (heading and pitch) determination of the prototype vehicle. These parameters are computed at the base station using the inverse

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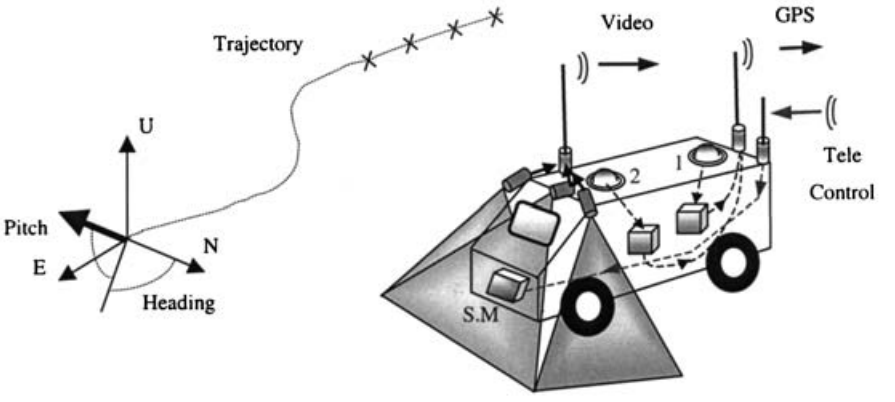


Figure 2. A telemetry-controlled unmanned test vehicle.

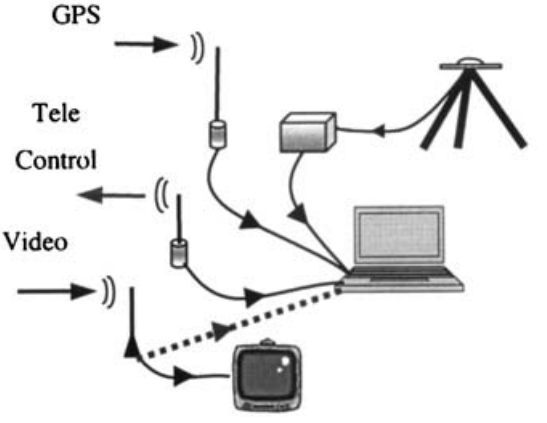


Figure 3. The Control Station at the Reference Site.

RTK approach. The GPS receivers are attached to two RTK radio-modems for transmission of their signals to the base (operating with different IDs),

(ii) colour, low-light level CCD cameras with good resolution, where multiple cameras were used to achieve a good level of vision in different directions,

(iii) a microwave video transmitter (noting that using a high-power transmitter may cause some interference with GPS signal reception),

(iv) receiver data link to get the telemetry commands,

(v) servo motors for changing the vehicle motion functions.

(b) The control station at the reference point (base) (Figure 3) to control the unmanned vehicle remotely. It is equipped with:

(i) the base GPS receiver, which occupies a point of known coordinates – its data combined with the received measurements of the two receivers mounted on the remote vehicle are used to estimate the position and attitude of the rover at the base station.

(ii) two RTK radio-modems to receive the GPS data of the two rover receivers onboard the remote vehicle,

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(iii) a video receiver to collect the video data sent from the remote vehicle,
(iv) a separate monitor for viewing video data or alternatively a dedicated video card or an external video bus (or a Dazzle) to convert the received video data on line to the laptop via a USB port, where it can be instantaneously viewed by the user using commercial software,
(v) a high speed laptop with large RAM and storage capacity to host the GPS data downloading, as well as to compute the rover position and attitude by the inverse RTK software, to view the video data sent from the remote vehicle, to store GPS data, and to generate the telemetric vehicle action required,
(vi) a wireless 'UHF' datalink to transmit the telemetry commands for controlling the motion functions of the rover.

There are a number of methods and equipment for transmission of video signals. Depending on the application, the selection of frequency and power requirements must be taken into consideration. Commercial surveillance systems can be used for this purpose, which have output power ranging from 10 mW to several watts; however, licensing might be needed when transmitting at high power. The video link used in testing of the trial system utilised 2·4 GHz digital video transmitters and receivers with an output power of 500 mW, and operated using 12 v DC batteries. The video transmitter and the receiver were a few centimetres in size. The colour cameras used have good resolution and can handle low light levels. The antenna employed for capturing video signals was a high-gain directional antenna. The higher the gain of the receiving antenna, the more directional it becomes; however, if it is too strong, the picture will start ghosting. The received video data can be displayed on a separate monitor or on the central laptop. It can also be stored and time-tagged with GPS timing for further processing; however, this will put a lot of processing and storing burden on the field laptop. The storage space needed after file compression will depend on image quality, image size, and recording rate.

The range for inverse RTK, video link, and telemetry data is governed by conditions of the path between the transmitting and receiving units. Thus, to increase the base-to-rover range, a video booster amplifier of 12 v DC power was used and the receiving antenna was set high up. Similarly, for the datalink, this was accomplished by using repeaters and the deployment of roof-mounted antennas on the rover.

In this research, programmable micro-controllers receive signals representing the telemetric control of the vehicle from the radio datalink and feed information to servomotors to control the basic functions of the rover motion. This includes changing the torque and angular velocity of the steering 'wheel' of the vehicle (right or left), braking, and acceleration control. A telemetric code was also sent to control the ignition (on/off) of the rover. Alternative systems can be designed according to type and weight of the rover vehicle and the application needed.

In the future, sophisticated unmanned vehicles should also contain ADAS in case the telemetric commands from the control station are lost. Positioning can then be performed using predicted phase corrections applied to the raw data or via a DGPS approach employing the pseudo-range measurements. The ADAS systems can control the vehicle motion so that it reacts to the precise road conditions and executes programmed missions. De Pedro *et al*. (2001), proposed a system for this task with driving strategies implemented by fuzzy systems, based on the GPS data and geometry of the

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site from previous maps or built from the captured video. The system models the behaviour of a driver or similarly, a remote controller by IF … THEN rules that meet the driving and environment conditions. The output will be automatic steering angles and acceleration values that the vehicle will follow without human intervention. These systems however are still in the development stage, and it is expected that a fully mature system will be available within the next few years.

4. POSITIONING AND ATTITUDE DETERMINATION. In the proposed inverse RTK system, the positions of the two antennas 1 and 2 (shown in Figure 1) should first be determined. The use of two independent antennas onboard the vehicle offers redundant information to help in case of data loss from either system. In addition, the distance between the two antennas, measured beforehand, is used to check the GPS solutions at both antennas by comparing the known length with the computed one, derived from the GPS solution. The height difference between the two antennas can also be computed from the known distance between the antennas and using the attitude data. This difference can be compared to the computed one from the GPS solution to check for the consistency of the height differences.

After position determination, the attitude pointing parameters (heading and pitch) can be computed. However, to determine these parameters accurately, the vector 1–2 should be determined at the mm level of accuracy. To reach this accuracy, the vector was recalculated taking the rear antenna (1) as the reference. In this case, the antenna spacing is very small compared to traditional GPS positioning, and thus, all correlated errors are practically eliminated in the differencing process.

The resolution of carrier phase ambiguities for the baseline vector 1–2 is aided by the knowledge of the positions of the antennas 1 and 2 by the inverse RTK positioning, which is accurate to the cm level, and thus, can be used to determine an approximate orientation of the baseline 1–2. This approximate orientation, in addition to the constraint built from the *a priori* knowledge of their baseline accurate length, is used to efficiently limit the search for the correct set of ambiguities and increase the solution reliability. Ambiguity determination thus becomes simple and fast as the number of candidate phase-ambiguity sets will be limited. In most cases, it can be directly determined from the estimated antenna positions, depending on positioning accuracy. The length constraint can be written as:

$$b_{1-2}^2 - \Delta X_{1-2}^2 + \Delta Y_{1-2}^2 + \Delta Z_{1-2}^2 = 0. \tag{4}$$

where:

b_{1-2} is the known baseline length between the antennas 1 and 2, and (ΔX_{1-2}, ΔY_{1-2}, ΔZ_{1-2}) are their baseline vector components in the WGS-84, based on the tested candidate ambiguity sets.

After solving for the carrier phase ambiguities and determining the antenna vectors in WGS-84, the vector components are transformed to the local-level coordinate frame (ΔE, ΔN, ΔU). Next, the heading and pitch of the rover platform can be directly estimated from the local-level antenna vectors as follows (El-Mowafy, 2001):

$$\text{Heading} = \tan^{-1} \frac{\Delta E_{12}}{\Delta N_{12}}, \tag{5}$$

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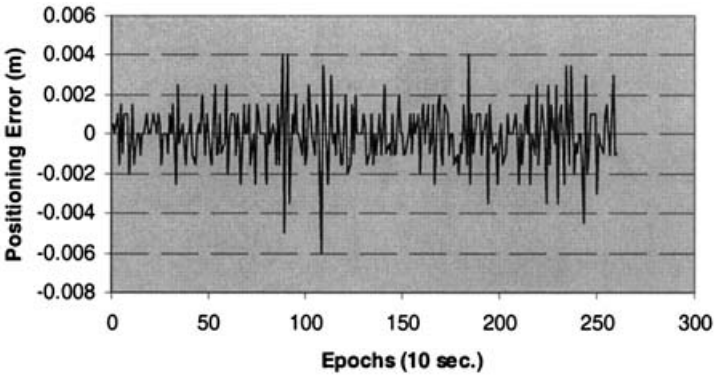


Figure 4. The zero-baseline test results.

$$\text{Pitch} = \tan^{-1} \frac{\Delta U_{12}}{\sqrt{(\Delta E_{12})^2 + (\Delta N_{12})^2}}. \tag{6}$$

5. TESTING OF THE INVERSE RTK SYSTEM. To assess the system performance, a zero-baseline test and two field tests were conducted. During testing, the inverse RTK processing was carried out by a laptop at the base station. The GPS data at this station were downloaded on line while data from the two receivers at the rover were received by the radio-modems and downloaded to dedicated cards connected to the laptop. All data were processed according to their GPS time stamps. The video data received from the rover was viewed on line, stored, and synchronised to the rover positions by synchronising the laptop time to the GPS time using the GPS-PPS timing of the reference receiver. Some basic telemetric control of the vehicle motion was also carried out to evaluate performance of this part of the system. Results of the tests given in the sections that follow will focus on the performance of the inverse RTK approach for position and attitude determination, as this was the main objective of this paper.

5.1. *The Zero-Baseline Test*. Preliminary testing of the inverse RTK approach was carried out using a zero-baseline test. The purpose was to check for the presence of any unaccounted for biases in the developed algorithm. In the test, the rover and reference receivers were connected to the same antenna. A radio with a low transmitting power of 2 watts was used, and the antennas and radios were separated as much as possible. A total data span of 2600 seconds consisting of 260 epochs with 10 seconds intervals was studied. The baseline length was computed in a post-mission mode from the computed positions.

The zero-baseline test results, illustrated in Figure 4, showed that the positioning error (expressed as the baseline length) was random in nature with an approximately zero mean. The error was generally less than 2 mm, which is well within the expected level of receiver noise, and thus no significant biases can be assumed in the processing algorithm.

5.2. *Field Testing*. During field testing, the system was setup as described above with the rover antennas 1 and 2 mounted on the roof of a prototype vehicle with 1·2 m spacing and aligned along the vehicle centerline. The data acquiring and processing

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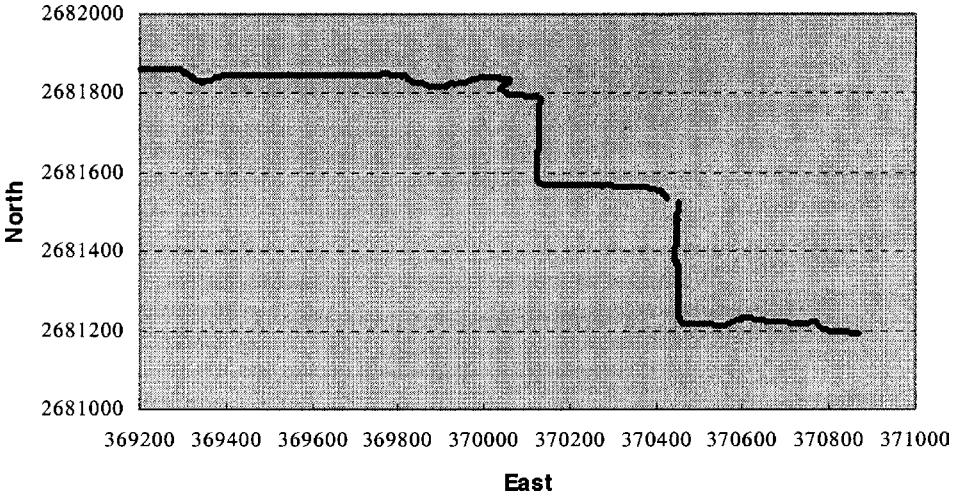


Figure 5. Trajectory of the first test.

rate was set to 2 Hz, with a cut-off elevation mask angle of 10 degrees. Two tests were performed. In the first, the number of GPS satellites observed ranged between 5 and 7 in clear areas, with PDOP values between 1·3 and 4·8. In this test, short ranges between the vehicle and the reference were considered, where the maximum range was almost two kilometres. In the second test, relatively longer ranges were considered (up to 4·13 km). However, in this case, only positioning and attitude determination from the inverse RTK approach were investigated without telemetric control of the vehicle. A radio-modem of 35 watts was used in this test; based on the author's experience, the use of the less power radio-modem available for testing (a 2 watts transmitter) could not serve reliably for distances larger than 2 km, noting that this range may vary according to the measuring environment. The number of GPS satellites observed in this test ranged between 5 and 9 in clear areas, with PDOP values from 1·4 to 3·9. The first test was performed in an urban area, and the second test was conducted along a highway in Al Ain, UAE. The urban area includes one to two-story buildings, and trees of heights varying between 4–7 m on both sides of the roads that the test vehicle passed through. Figure 5 shows the trajectory of the first test, where coordinates are represented in the local coordinate system (UTM with Clarke 1880 ellipsoid).

The precision of the internal positioning of the developed inverse RTK approach was determined from the statistical information of the Kalman filter processing. Table 1 gives a summary of the average errors of antenna 1 and antenna 2 for the two tests. Results of the second test were less precise than the first test, and that can be attributed to increasing the rover-to-base distance. For both tests, the standard deviations of the plane coordinates were generally less than 3 cm, and less than 4 cm for the total plane positioning error. However, as expected, the height precision was less as its average standard deviation reached 5 cm. It is clear that for the tested ranges, the average precision for the two tests were very comparable. Table 2 thus summarizes the achieved overall statistical information on the precision of the system positioning under testing conditions. Figure 6 illustrates the frequency histogram of error distribution for the two tests. It is clearly shown that the majority of errors lay in the range

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Table 1. Statistics of the inverse RTK positioning accuracy.

Coordinate	First Test		Second Test	
	$\sigma_{Average}$ (cm)	RMS (cm)	$\sigma_{Average}$ (cm)	RMS (cm)
E	1·75	0·19	1·95	0·82
N	2·76	0·36	2·97	1·38
H	3·23	0·55	4·96	2·20

Table 2. Descriptive Statistics of the Total Plane Positioning Errors.

Mean	Mode	Std. Deviation	Kurtosis	Range
3·40 cm	3·16 cm	1·03 cm	7·50	9·84 cm

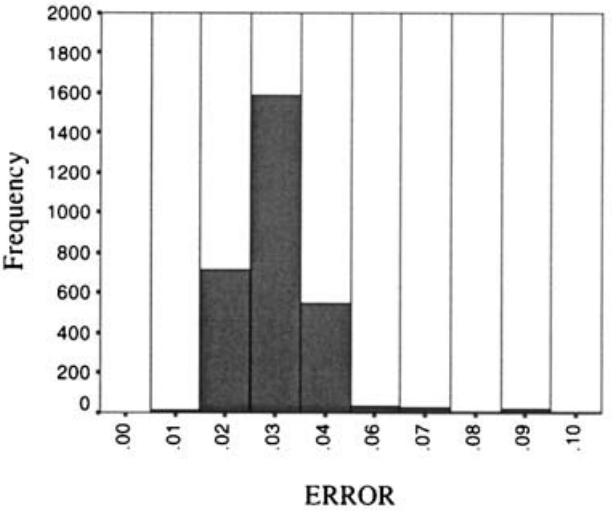


Figure 6. Frequency distribution of positioning errors.

2·5–3·5 cm, with significant errors between 1·5–2·5 cm and 3·5–4·5 cm. Other than these values, the number of errors that occurred is relatively very small.

The plane positioning errors drawn versus the reference-to-rover ranges are depicted in Figures 7 and 8 for the first and second tests, respectively. Figure 7 shows that the accuracy was more or less consistent throughout the whole survey. The large errors at the start of the survey (for the first 500 m), shown in Figure 8 for the second test, can be ascribed to the low number of satellites observed for this period, as well as to multipath errors. Multipath errors were predicted due to the fact that the vehicle was moving very close to a huge building (a shopping mall) with surfaces mainly made of glass, which represented a major source for signal reflection. Dispersion of errors is also significant in Figure 8, particularly for longer ranges. However, the errors were generally bounded between 2 cm and 4 cm for most of the survey.

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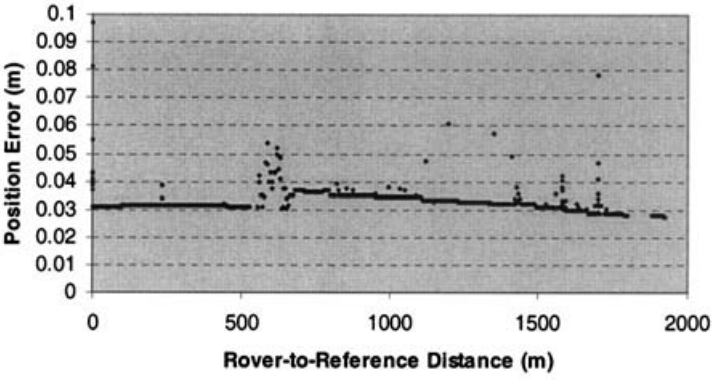


Figure 7. Plane positioning errors (first test).

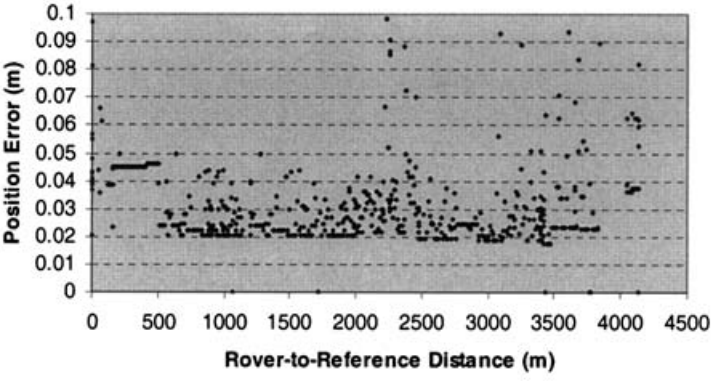


Figure 8. Plane positioning errors (second test).

To assess accuracy degradation due to latency as well as to check independently the performance of the inverse RTK software, the carrier-phase measurements of the two rover receivers and the base were collected on line while testing and stored in the internal memory of the receivers. After completion of the field survey, the carrier-phase measurements were processed in a post-mission mode and their derived positions and attitude were compared with results of the inverse RTK method. These results, as described above, were determined with rover receivers measurements predicted using a rapid approach to the epochs of the reference measurements. Results of the comparison are presented in Table 3, giving the average values for errors in the plane and height coordinates for the two tests. Positioning differences in all coordinates were generally less than 1 cm. Firstly; this proves that the developed inverse RTK algorithm performed well with no major errors either in ambiguity resolution or in position determination. Second, the latency errors according to the used equipment, particularly the radio-modems, receivers, and the software are limited to 1 cm. This error can be further reduced with improvements in software coding and hardware.

As expected, since attitude determination is irrelevant to the rover-to-base range, the precision achieved was similar for the two tests. The overall accuracy of attitude determination (heading and pitch) for the two tests is given in Table 4. The impact of

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Table 3. (Post-Mission – Inverse RTK) Positioning Differences.

Coordinate	Average Difference (cm)
E	0·86
N	0·79
h	0·95

Table 4. GPS attitude accuracy.

Orientation Parameter	σ_{Average} (degrees)
Heading	0·201
Pitch	0·312

multipath errors seen at the beginning of the second test was not significantly visible in this case, as the two antennas 1 and 2 were onboard the vehicle, and experienced the same errors. Thus, these errors were generally eliminated when differential positioning was carried out between the two antennas in order to determine their vector components, from which the attitude was estimated. The average of the absolute attitude errors in heading and pitch were 0·201 degrees, and 0·312 degrees, respectively. As expected, pitch estimation was less precise than the heading due to inclusion of the height ordinate in the computation of pitch. These accuracies were estimated under the specific baseline length and configuration used in this test. However, better performance could be achieved if baseline length was increased. The instantaneous ambiguity resolution was achieved with full success using the approximate baseline orientation estimated from the two antenna positions (1 & 2) derived by the inverse RTK technique aided by the information of the known baseline length.

6. CONCLUSIONS. The concept of the inverse RTK positioning was presented in this study demonstrating (as a model) the telemetric control of a remote unmanned vehicle using its video data and position and attitude (orientation) information computed at the base station by the inverse RTK method. Two receivers were used on the rover for increased positioning reliability and for determining the heading and pitch of the vehicle. Testing of the system proved that there were no biases due to algorithm modelling. Latency due to the presented system architecture produced positioning errors of less than 1 cm with a potential for improvement.

Results showed that plane positioning accuracy of less than 4 centimetres could be generally obtained with distances less than 4 kilometres if the number of observed satellites is 5 or more and PDOP less than 5. The heading and pitch of the vehicle were generally determined within 0·2–0·3 of a degree using a 1·2 metre baseline between the on-board dual antennas. Better heading determination can be achieved as the baseline length increases. In addition, the proposed method of using the approximate orientation of the baseline, computed from the inverse RTK determined positions, to set the search region for phase ambiguities in the instantaneous attitude determination proved to be efficient. It abolishes the need for other methods, which employ an array of closely spaced antennas, or which use external information from other sensors, such as dead reckoning systems.

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