HOLEINONE FINAL REPORT

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Name, title and organisation of the scientific representative of the project's coordinator:
THE UK INTELLIGENT SYSTEMS RESEARCH INSTITUTE LIMITED (in liquidation)
Liquidator: Mr. Darren Brookes
Contact: Ms. Molly Monks
Milner Boardman & Partners
Tel: +44 161 927 7788
Fax: +44 161 941 3038
E-mail: mollym@milnerboardman.co.uk

Project website address: http://www.holeinone-project.eu

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1. Final publishable summary report

1.1 Executive summary

Pothole repair in road networks is one of the most commonly performed operation for most road maintenance teams, especially in areas where cold winters and wet springs contribute to accelerated road surface breakup ever year. The poor condition and lack of maintenance of European roads contribute to at least one third of all accidents each year, and accounting to 52.7% of fatalities in 2011. Potholes also hold the distinction of being the most aggravating road distress to the traveling public in general.

Pothole repair generally accounts for a significant portion of transportation departments' operating budget, with more than €1,2 billion being directly attributed to fill nearly 20 million potholes in Europe during 2011, but only half of Europe's potholes were treated. This can be attributed to the high initial costs associated with maintenance activities, the historically poor performance of patching which often necessitates additional maintenance work, and the exorbitant safety and legal costs associated with the need for traffic control of these activities. As such, any improvements or advancements in this area could result in substantial cost savings.

As a response to this need, a pothole repair method that will significantly reduce the direct costs (cost of repair) and indirect costs (cost of user compensation, traffic disrupts, etc.) associated with road maintenance activities is required. Specifically, increased effectiveness and better productivity during pothole repair and enhanced longevity of potholes use are required.

Hole-in-One, in direct response to this need, aimed to develop a fully automatic, via robotic vision and computer-control, and adaptive, via an expert system, pothole repair system with integrated quality assurance mechanisms, as well as a new, robust patch material blend - an emulsified asphalt emulsion - that lend itself to the automatic process and demonstrates excellent performance.

The project was terminated prematurely. However, two of the planned developments were successfully carried out. A novel machine vision system leveraging 3D stereo vision technology was designed and implemented. Moreover, an innovative repair material blend was produced based on extensive research for full characterization at laboratory scale.

1.2. Summary description of the project context and the main objectives

The core objective of the Hole-in-One to produce a robotic system that will be able to streamline and automate the pothole repair process, giving rise to a significant business opportunity by effectively addressing crucial technology-based and market-driven challenges.

Potholes represent a consistent and re-occurring problem impacting EU road networks. Despite the fact that focus is put on the most extreme potholes, current costs to governments are still excessively high. More than €1,2 billion was directly attributed to fill nearly 20 million potholes in Europe during 2011. However, approximately 50% of potholes were left untreated, which also left a growing backlog of unresolved cases. The estimated time to clear current carriageway maintenance backlog, with existing budgets, is currently at more than 10 years. In addition, the amount paid in user compensation claims (resulting from potholes) rose in €289 million in 2011, while 644.632 staff days spent dealing with these claims raising the total cost (compensation reimbursement and labour expenses) for European authorities to €471 million.

Although the main costs result from road repairs these are compounded by additional problems. A significant number of incidents result from potholes. According to a study by the International Road Federation (IRF), poor condition and lack of maintenance of European roads contribute at least to one third of all accidents each year. According to IRF, accidents that are caused by or in part due to roadway conditions accounted for 38.2% of nonfatal injuries (1.5 million cases) and 52.7% of fatalities (34,500 deaths) in 2011.

The root of this problem is infrastructure investment and reactive maintenance budget. Although engineering know-how and technology to build super-solid roads, all the time, any place, are available, the capital needed is not. Therefore, many local roads are evolved structures and are of thin construction. In addition, there is little residual engineering capacity in the local road network, and thus is maintained in a state of limiting equilibrium. In this condition, if catalysts occur (such as poor weather conditions, ineffective or no repair of existing potholes, insufficient routine, periodic or reactive maintenance), the network is vulnerable to the development of potholes.

As road maintenance budgets are limited and reactive maintenance is reduced or prolonged, the potential for the development of potholes during wet weather increases significantly. The main objective in reducing pothole formation is thus to ensure that reactive maintenance is applied timeously and to the appropriate standards. Also, given the on-going debt crisis in Eurozone coupled with the global recession fears, authorities must work hard to squeeze better value from shrinking funds. This is, however, unlikely to be achieved fully with existing technology and new, more effective and of increased productivity, techniques for repairing potholes must be implemented. Getting road network into reasonable condition is vital to keeping Europe moving, allowing services to function efficiently, and helping local economies flourish.

Existing pothole repair techniques present significant drawbacks. The throw-and-go method it is the most commonly used method because of its simplicity and high rate of production. Throw-and-roll is considered a superior alternative, applying a patching material mix with proprietary asphalt additives, to the traditional throw and-go method. However, they both involve excessive manual labour to repair, involving site assessment, preparation of the hole and application of either standard (temporary and faster) or proprietary (longer term and long-lasting) patching materials. This is labour intensive and slow, leading to longer disruptions, higher cost, and creating heightened safety risks – due to the presence of traffic, and elements of processing (heat, fumes, vibration – manual equipment). In addition, the patch failure rates are significantly high (at the range of 27-29%), while the expected patch survival period is short, 3 months for the standard mix and up to 12 months for the proprietary one. This, in turn, increases the effective patching operation cost.

Semi-permanent repair procedures achieve lower patch failure rates are lower (circa 18%) and the expected patch survival period exceptionally long (30 months), the overall cost of the patching operation is even higher inhibiting performance.

To deal with the increased labor costs, several agencies use systems that provide a more automated method, such spray-injection devices, for repairing potholes. However, initial costs can prohibit use and there are some major restrictions on use as they all still require significant manual input. This technique has higher equipment costs than the other procedures, but it also has the highest rate of productivity and lower material costs.

Another method used by some agencies during the last years is the infrared patching method. This method employs infrared rays to allow deep asphalt penetration (and heat) and reclaiming asphalt without causing damage to the material being reclaimed or to the road which is being heated. The overall performance (expected failure rates and expected patch survival) of infrared patching is better than average. The trade-off is the lower daily productivity mainly due to the fact that one should allow infrared to penetrate for approximately 10 minutes, a considerable amount of time, depending on depth, season, and aggregate, before the actual repair takes place.

In summary, the time taken to treat potholes is typically excessive and constitutes the main drawback within exiting solutions. Although times as low as 10 minutes (physical treatment) are reported with current state-of-the-art equipment, this is dependent on a number of criteria, e.g., when no additional excavation is required, perfect weather conditions, etc. The reality is that the total time for site survey, site preparation, treatment, and review is significantly longer (circa 30mins - several hrs); this heightens the burden on responsible stakeholders, which have to deal with a high number of road repairs and contributes towards significantly longer response times. There is also a direct impact on traffic disruption which occurs during repairs.

In addition, all of the emerging solutions found during our literature research share the same major limitations: a) their use is impeded by current conditions, including climate, for instance, cold and damp conditions are not conducive to quality results and the number and/or frequency of re-repairs can be substantial, and b) none of the existing potholer repair technologies is quality assured.

Hole-in-One consortium will follow a holistic approach, studying the functional relationship between parts and the whole, aiming at optimizing productivity (make it fast and cheap) and performance (right first time & last for long) “globally” to reach further than any commercial solution currently available. The proposed, Hole-in-One, solution will incorporate:

- A fully automated machine, via robotic vision and computer-control, for unattended (assuming one supervisor only and no repair crew) operation at all stages, including site assessment hole preparation and patch application, and under any conditions (day and night, dry or wet, warm or cold).
- A repair process and a new emulsified asphalt emulsion1 that lend themselves to full automation.

Emulsions used will be properly matched to the aggregate in-situ and the most suitable mix will be used extending longevity of use. Site, pothole and climate conditions will be taken into account during pothole treatment to ensure the best possible result.

- Integrated in-line quality controls (hardware and algorithms) at both the low-level (process tasks, e.g., cutting, patching, etc.) and high-level, i.e., the repair process as a whole, to check quality at real-time and command corrective actions to guarantee the final outcome, thus reduce failure rates and avoid re-works.
- An expert system, comprising an inference engine and a knowledge base, to facilitate the computer-aided evaluation and decision support process.

1.3. Description of the main S & T results/foregrounds

The Hole-in-One project produced two outcomes that significantly push the state of the art. This is the result of intensive research in the fields of patch blend materials and 3D computer vision.

Hole-in-One patch blend material. The fundamental research on materials carried out as part of the project produced a novel patch blend material of the cold asphalt type. The performance of the Hole-in-One cold asphalt material was thoroughly assessed in various lab tests. As mo common regulations or requirements for these materials were found throughout Europe, evaluation test methods were selected according to existing European Standards. However, the conditions, particularly temperature, were adjusted for some test methods in order to assess the more specific requirements of pothole maintenance, specially when cold lay materials are used. The proposed deviations from the standards methods were based on the experience gained in the field of cold asphalt materials and Instarmac's (partner of the project) recommendations.

In the study the Hole-in-One material was fully characterized and properties compared with two traditional solutions for reference purposes. These are two cold lay materials currently available in the EU market from different suppliers, named as A and B. The Hole-in-One material is a bitumen based product in which the liquid binder has incorporated vegetable oils. Reaction is promoted by the presence of a reactive polymer which is activated by the presence of air.

The tests conducted were divided into basic and supplementary tests as shown in the following table. Test of particle size distribution, binder content, indirect tensile strength, water sensitivity and Cantabro were selected as the basic tests. Other tests, as wheel tracking and stiffness modulus tests were selected for a deeper investigation.

Table 1: Recommended tests for laboratory investigation

Basic tests		Test method
1.	Aggregate gradiation and maximum size of aggregate	EN 12697-2, EN 933-1
2.	Binder content	EN 12697-1
3.	Indirect tensile strength	EN 12697-23
4.	Water sensitivity	EN 12697-12
5.	Cantabro test (particle loss)	En 12697-17
Supplementary tests		
6.	Wheel tracking test	EN 12697-22
7.	Stiffness modulus	EN 12697-26 (Annex C)

The experimental procedure for the preparation of the samples was the same as the one for hot asphalt. Once prepared were stored for a week or two, depending on the test, at 45ºC to let them cure, before application of the relevant test procedure.

The table below shows a summary of the results obtained for each of the samples evaluated.

Table 2: Summary of the test results

Test	Reference solution A	Reference solution B	Hole-In-One
Binder content (%)	5,1	5,7	7,6
Moisture content (%)	3,8	0,91	0,33
ITS @ 20 °C, 1 day (%)	*	0,04	0,06
ITS @ 20 °C, 7 day (%)	*	0,16	0,16
ITS @ 20 °C, 14 day (%)	*	0,28	0,24
ITS @ 5 °C, 7 day (%)	*	0,1	0,24
Water sensitivity (%)	96,14	97,68	97,83
Cantabro -Particle loss (%)	**	13,25	4,74
Rut depth (mm)	*	**	0,267
Stiffness (MPa)	*	1320	859

* Not enough sample to complete the test campaign

** Could not be performed as most of the samples stated soft after compaction, with little or no resistance to loading (and some of them even disintegrating spontaneously).

According to these results the following conclusions can be drawn:

- Indirect tensile strength (ITS) values show that the Hole-in-One sample offered a better performance than the reference ones, at shorter curing times and at severe conditions. Please, not that a higher tensile strength corresponds to a stronger cracking resistance.
- Values of water sensitivity indicated a good cohesion between binder and aggregates under wet conditions, as in all the samples tested are above 90%, minimum value according to the specifications.
- Results from Cantabro test shown that the Hole-in-One cold asphalt offers better performance than the reference material (particle loss of 4,74% in comparison with 13,25%).
- In order to determine the permanent deformation behavior of asphalt the wheel tracking test was performed. This test determines its response at high temperature and long loading time. Rut depth from the wheel tracking test gave an acceptable value only for the Hole-in-One sample; for the reference samples the test could not be successfully completed.

As a summary of the study it can be stated that only the Hole-in-One material had values of indirect tensile strength, water sensitivity and wheel tracking that were close to the hot asphalt values

The Hole-in-One 3D Machine Vision system. Within the scope of the project we have produced a 3D vision system based on stereo vision technology. The system has been proven to achieve accuracy of <2mm in distances of 60-120mm. It is used for automatic pothole detection and distance measurement for quality control.

The Hole-in-One 3D Machine Vision system is highly innovative in the following respects:

- It makes use of advanced texture filtering techniques that significantly push the boundaries of texture-based segmentation. These algorithms are powered by novel wavelet-based approaches.
- It leverages a proprietary stereo matching algorithm that is fine-tuned for short distance stereo vision enabling unprecedented accuracy in depth measurement of texture-rich surfaces with no need for light patterns. The algorithm is parallelized and runs in real-time in a commercial GPU-enabled single board computer.

The Machine vision system presents significant market potential in service robotics applications that require advanced perception capabilities thanks to its small form factor and high performance-to-cost ratio.

An illustration of the pothole detection and depth measurement results is shown in the two images presented below.

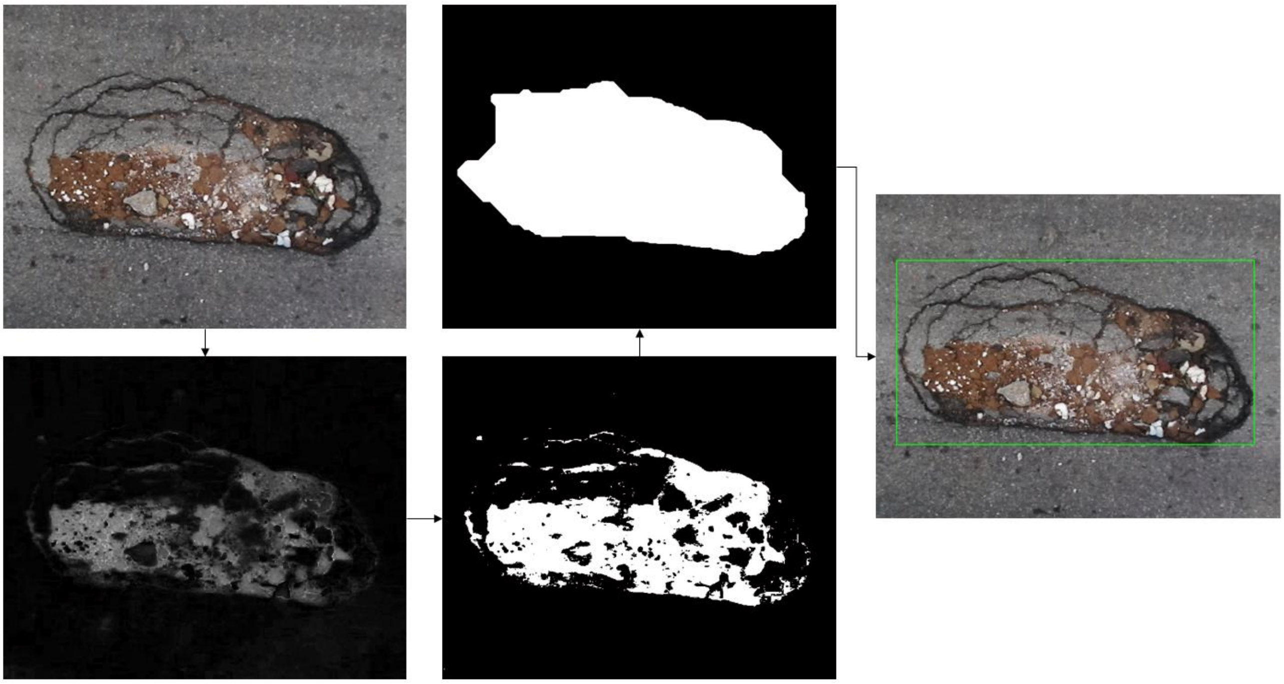

Figure 1: Pothole detection results

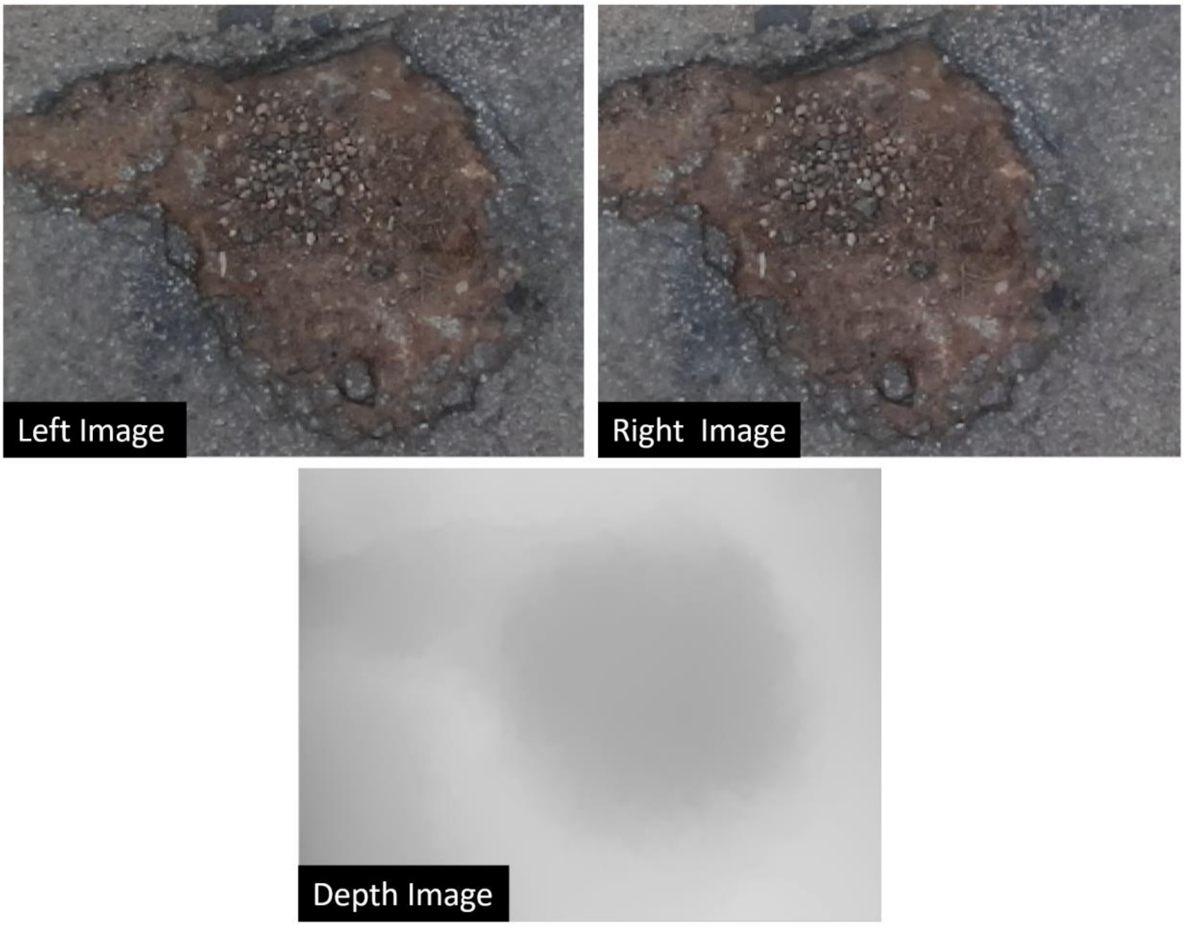

Figure 2: Pothole depth measurement results

1.4. Potential impact

At this point, only two of the project results have been successfully produced. The Hole-in-One solution, once fully complete, has the potential to achieve faster and cheaper pothole repairs under any conditions. In addition, the repair task will be done right first time and the pothole patch will last for longer. A conclusive summary of our cost-benefit analysis carried out outlines that the proposed automated pothole repair would have the following productivity, and directly related to cost, advantages over existing alternatives:

- Lower cost: two thirds the cost for spray and infrared patches and half the cost for permanent ones.
- Extended survival rate: by one third of permanent patches survival rate and by half of infrared ones.
- Half the cost for traffic control; Hole-in-One will operate as a moving work zone integrating traffic signs.
- Availability: operate three shifts per day, at times of lower traffic, such as night, and up to 260 days a year.

The average number of potholes filled by authorities Europe during 2010/11 represents a 59% increase compared with the previous year, which was itself 42% higher than the year before. These large increases indicate the severity of the damage caused by severe weather at the start of 2010. The average cost of filling a pothole estimated by English authorities has actually fallen from last year, possibly as economies of scale cut in. “Better repair measures and efficiencies” and “good management information” were factors, offered by focus group participants as reasons, for the reduced average cost of filling a pothole in Europe. However, the overall cost has increased in, and the total amount spent in filling potholes across England and Wales has increased by 16% since the previous year.

The ideal frequency of road resurfacing, taking into account the lifespan of surfacing materials, the type of road, and its level of traffic, is between 10 and 20 years. This maintains an appropriate level of grip, vital for road safety, and guards against freeze-thaw effects by maintaining a weatherproof seal on the road surface. Only Northern Europe comes close to this ideal, on its principal roads due to permafrost in several occasions2. Other European authorities fare less well with principal roads estimated length of time before roads are resurfaced averages to 33 years, to non-principal roads estimated to have to wait 65 years on average before being resurfaced and surfaces of unclassified roads having to last for an average of 115 years. The averages for Europe (including Northern Europe) have increased (more years between resurfacing) since last year for all road types.

According to IBIS World’s Road & Highway Maintenance market research report (NAICS 23411b, Oct 2011), European governments expenditure will support industry growth over the next five years (2011- 2016). Based on 2006-2011 figures, the Road Maintenance industry experienced a 3.8% annual growth to reach €46 billion in 2011. A total of 9,445 businesses are involved in this sector, employing more than 170,000 people. Most importantly, there are no companies with a dominant market share in this industry.

We estimate that payback will be very attractive to interested stakeholders, e.g., maintenance contractors, government highway agencies, cities, and municipalities. In Section 3, where our full cost-benefit analysis is presented, we calculated the cumulative (4 years after project end) revenue and profit (€151m and €66m, respectively) and the return on investment (66:1), where both include the grant that we request and post-project commercialization costs (~€0,8m), for three different scenarios of small, medium and large potholes, to conclude that the ROI break point could occur after less than two years making moderate assumptions.

In addition, we estimate, assuming a very modest daily average patching of 60 potholes for a two-shifts maintenance team, daily savings between €2,246 and €4,349 depending on the current technique to be replaced. On an annual basis, that corresponds to repairing 1.5 million potholes for a country like the UK, accumulates to potential savings of €108.74 million, or €140.89 million if user delay costs are considered, if it was to replace a conventional technique (throw-and-roll procedure). Extending this calculation to Europe, and assuming a modest 10 million potholes treated, potential savings from adapting the Hole-in-One technology can reach slightly less than €1b. The latter also indicates that the existing backlog of unresolved cases (approximately 50% of potholes are left untreated every year), will clear within 1 year without adjusting the budget for road maintenance!

1.5. Address of the project public website

www.holeinone-project.eu