NDT Sensor Fusion: Optimisation of NDT Sensor Data Processing Strategies for Road Infrastructure Inspection

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Abstract

The European Road Network (ERN) is undoubtedly one of the most important land infrastructures in the EU. Consisting of a wide variety of types of roads and motorways, it is and will remain for the foreseeable future a crucial artery for Europe. Transport infrastructure is fundamental for the smooth operation of the internal market, for the mobility of persons and goods and for the economic, social and territorial cohesion of the European Union. However, the most important factor for the quality of the ERN is maintenance and it is considered to be the most expensive function of a highway operating agency. As a result, there is a real need for an early detection of deterioration mechanisms and of potential presence of defects through a more advanced road infrastructure inspection technology. Therefore, the ultimate goal of EU FP7 RPB HealTec project (Road Pavements & Bridge Deck Health Monitoring / Early Warning Using Advanced Inspection Technologies) is to develop an integrated solution that would be able to reduce the maintenance costs and improve the performance by means of accurate and fast road inspection. Firstly, this paper presents a state-of-the-art overview of the current non-destructive testing (NDT) road infrastructure inspection methods and the existing commercial solutions. The proposed solution of the RPB HealTec system is based on fusion of the widely employed and novel NDT sensors such as the ground-penetrating radar, infrared thermography, air-coupled ultrasound and high definition video cameras. The paper also describes the proposed data acquisition methodology and provides an in-depth study of processing of NDT sensor data in the specific case of road infrastructure inspection. Based on this study an optimized strategy is derived with respect to the defined specific features of this problem domain.

1. Introduction

The European Road Network, which is estimated at approximately 5,000,000 km for the EU 27, is undoubtedly one of the most important land infrastructures in the EU, both in economic terms and social terms. However, the most important factor for the quality of the ERN is maintenance and it is considered to be the most expensive function of a highway operating agency. The total cost of road construction and maintenance is measured in tens of billions of euros (EC, 2015). As a result, there is a real need for an early detection of pavement deterioration mechanisms and potential presence of defects through optimisation of the road infrastructure inspection technologies.

As shown in Figure 1, well-timed preventive maintenance actions such as crack sealing, surface coating, or patching extend the road pavement lifetime by deceleration of the deterioration processes before the required rehabilitation or reconstruction works as well as improving pavement serviceability (Christopher, 2006). Accordingly, the regular road condition surveys for detection of defects potentially causing pavement deterioration reduce the costs of maintenance, the costs due to impedance of goods travel during maintenance periods, and the costs related to traffic accidents. The pavement condition is characterised with respect to the functional and structural aspects. The structural condition determines the structural capacity of the pavement from the measured layer thickness, structural changes, and material properties, while the functional condition assesses the ride quality based on the measurement of surface texture parameters and the presence of surface defects.

Although the road infrastructure also includes bridge deck and tunnel pavements, hereafter, this paper focuses on the road pavement condition surveys due to the specific requirement of this problem domain related to the large scale of the required data recording and information processing. In general, because of the varying and constantly changing international standards of pavement design and rehabilitation procedures (Figure 1) as well as the limitations related to the vast amounts of data, development of the universal survey guidelines or tools is a complex task. There is a number of commercial off-the-shelf survey equipment systems successfully utilized in the highway community, however there is a clear need for further optimisation and development of NDT sensor-based systems that cover both the functional and structural road pavement condition for efficient maintenance planning.

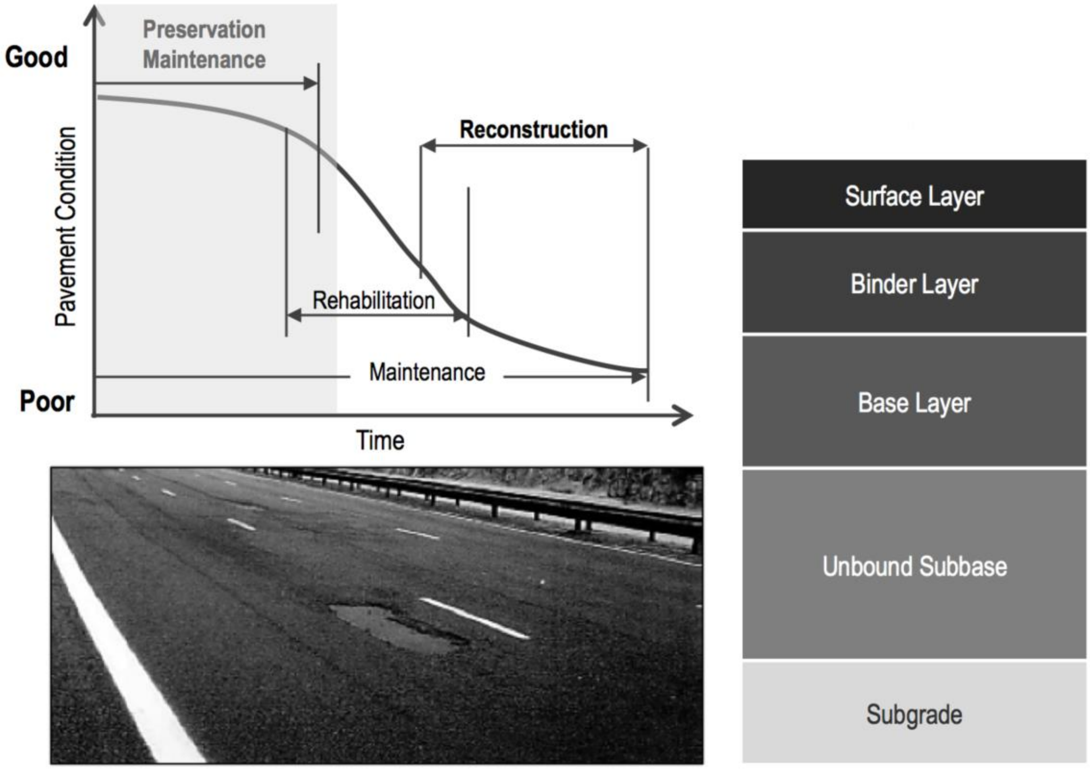

Figure 1. Flexible road pavement life cycle and general layer structure

The ultimate goal of the FP7 RPB HealTec project (RPB HealTec, 2015) is to develop an integrated multisensor NDT solution for the maximum multidimensional coverage of pavement condition that would improve the performance of individual sensors as well as providing fast road inspection at traffic speeds. The corresponding identified optimal set of sensors includes ground penetrating radar (GPR), infrared thermography (IRT), and air-coupled ultrasound (ACU).

The rest of the paper is organized as follows: Section 2 describes the presently employed and approved road infrastructure inspection techniques with the focus on flexible road pavement condition survey. Section 3 illustrates the proposed RPB HealTec system solution for optimisation of structural pavement condition monitoring based on the fusion of NDT multi-sensor outputs. Section 4, concludes the paper and identifies the areas of further work.

2. Road pavement condition assessment strategies

As mentioned above, the road infrastructure inspection is conducted as a routine monitoring or planned maintenance procedure for the assessment of functional and structural conditions of pavement sections. The visual inspection is performed by a surveyor who manually registers the presence of surface defects in a report and grades their severity and extent in accordance with the standard guidelines (TRL, 2015). It remains the most common survey type. In addition to the various measurement tools, the corresponding survey methods also include high definition (HDV) recordings made from a moving vehicle in order to increase the inspection speed and the defect rating is performed after the data acquisition (VDOT, 2012). Generally, visual surveys are characterised by low inspection speeds and are highly dependant on the surveyor’s level of expertise. The list of some of the commons surface defects is given in Figure 2 including cracking, potholes, structural deformations, texture deficiencies, and patching.

The functional pavement condition survey for the assessment of ride quality and safety as well as the detection of surface defects is performed at traffic speeds by the vehicle-mounted sensor equipment such as laser profilometers, multiple HDV cameras, and skid resistance testers. The International Roughness Index (IRI) calculated from the laser measured longitudinal profile is widely employed in the pavement maintenance planning, while the transverse profile is used in detection and grading of rutting defects. The HDV and laser scanning are becoming the state-of-the-art solutions for evaluation of the surface macrotexture condition and the presence of surface defects. The examples of commercial multisensor survey systems for functional pavement condition inspection include the ROMDAS survey system (Data Collection Ltd., 2015) and the ARAN survey system (Fugro Roadware, 2015), which integrate multiple HDV cameras and laser profiler sensors.

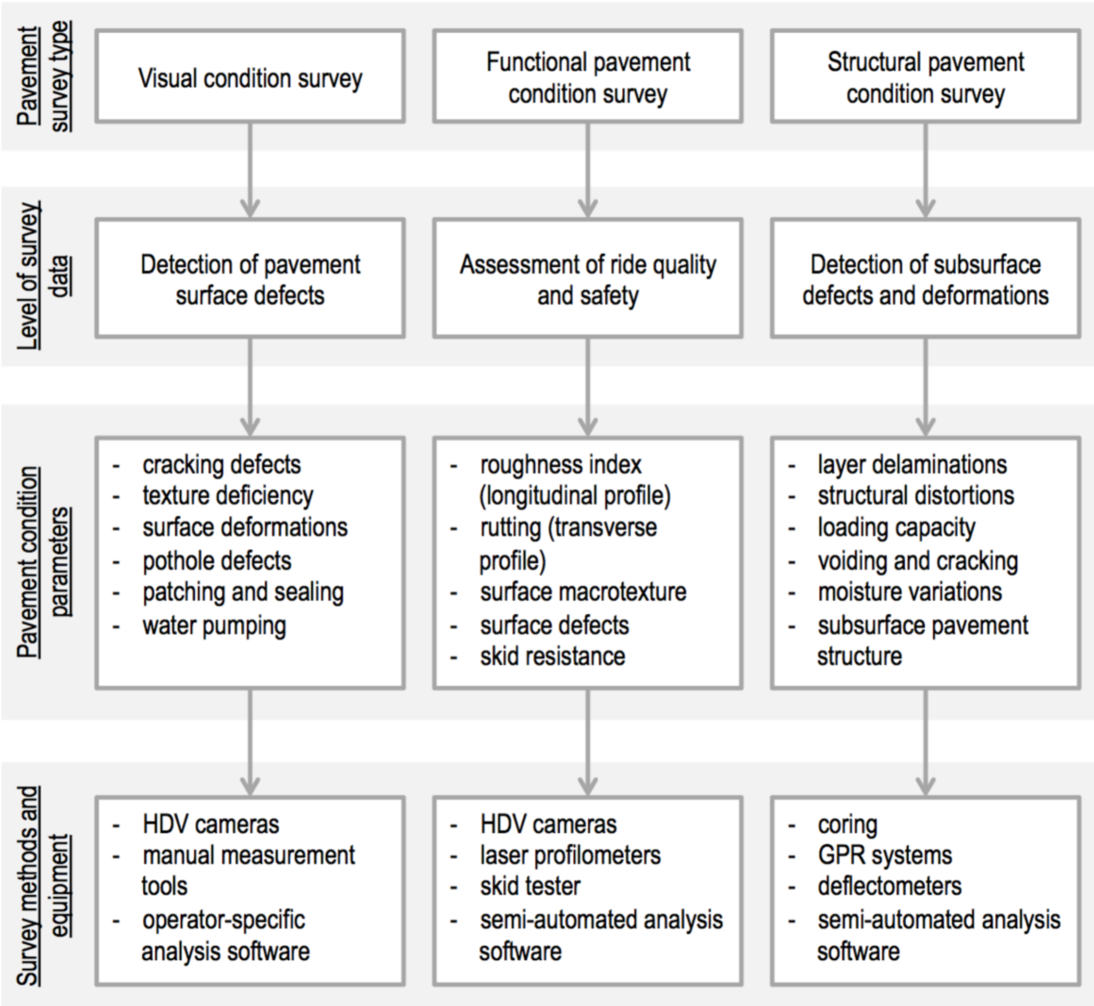

Figure 2. Road pavement survey types

The outputs of the structural pavement condition surveys are used for identification of changes in layer structure and material properties, monitoring of pavement subsurface, and detection of such defects as subsurface layer delaminations, cracking and voiding. The corresponding NDT sensors include GPR systems and deflectometers routinely employed along with the destructive coring procedure. For instance, the GSSI integrated solution (GSSI, 2015) consists of the vehicle-mounted GPR and falling weight deflectometers (FWD) sensors. The FWD measures pavement load bearing capacity at the areas of interest identified in GPR measured layer structure profile. The ARAN system also has an option to be extended with the GPR module for the subsurface pavement investigation such as layer thickness monitoring (Fugro Roadware, 2015).

Pavement management systems (PMS) use the road survey outputs for the planning of maintenance and construction works and road infrastructure monitoring. The functionally of PMS software covers storage, processing, and analysis of raw inspection data together with survey and preventive maintenance planning, asset management, and analysis of rehabilitation and reconstruction history (W.D.M. Ltd., 2015). Correspondingly, as shown in Figure 3, the required essential inputs for a PMS include: (i) road infrastructure construction and historical information; (ii) processed and synchronised survey data; (iii) Geographic Information System (GIS) map and video/photo referencing; (iv) traffic volume and environmental condition information.

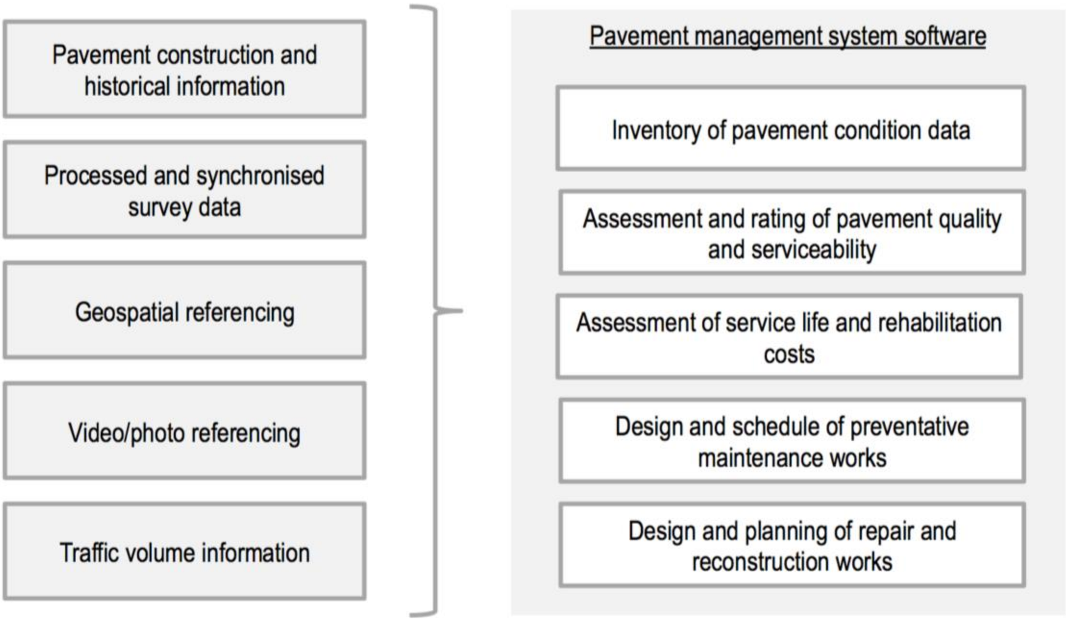

Figure 3. Pavement management system software inputs

3. Proposed RPB HealTec NDT multi-sensor system

The RPB HealTec system is aiming to upgrade and optimise the strategies of inspection of the European roads, thus reducing the maintenance costs and increasing traffic safety. This will be achieved by developing of a novel automated and integrated NDT system for traffic speed inspection of road pavement and bridge deck condition. The proposed solution illustrated in Figure 4 is based on the fusion of ground penetrating radar, infrared thermography, and air-coupled ultrasound NDT sensors, which produces multidimensional information on the road pavement structure thus extending the classical structural pavement condition survey methodology. The processing and analysis of survey data are performed after the data acquisition on the standalone software module producing the decision-support output for the pavement management systems.

In accordance with the established pavement inspection standards (Highways England, 2008), in road inspection, GPR systems with an array of antennas are used for the acquisition of information on the subsurface layer structure and material properties along with the pavement deterioration areas (Heitzman et al., 2013). However, the application of IRT and ACU technologies in road inspection is novel and mainly focuses on the shallow interface between the surface and binder layers. 2D thermography frames of pavement segregation are used for distinguishing of the vulnerable areas associated with subsurface delaminations or deterioration as well as detection of surface defects. Although thermography has proved to be efficient in bridge deck subsurface inspection (Washer et al., 2015) and detection of cracking defects (Solla et al., 2014) and is employed in several commercial systems (Penetradar Corporation, 2015), it is associated with high level of uncertainty in road pavement inspection (Heitzman et al., 2013). This is caused by the environmental factors and the properties of bituminous pavements and can result in false detection of subsurface defects and deterioration areas. In the RPB HealTec solution, this issue is resolved through the fusion the IRT output with the results of GPR and ACU subsurface investigation. Ultrasound is considered to be highly effective in detection of subsurface delaminations and voiding in bridge deck inspection (Gucunski, 2013). Recent advances in non-contact ACU technologies based on minimisation of the signal magnitude losses caused by the acoustic impedance mismatch (DR. HILLGER, 2015) resolved the speed limitations associated with the required sensor-surface coupling in classical ultrasound inspection. Non-contact ACU is highly sensitive to changes in both surface and subsurface conditions but is limited to the depth of the surface pavement layer. Based on the employed multiple physical phenomena, integration of these NTD sensor outputs extends the structural subsurface profile extracted from GPR data with the information on the interface between the bituminous layers of similar materials as well as providing the additional information for the full road lane coverage.

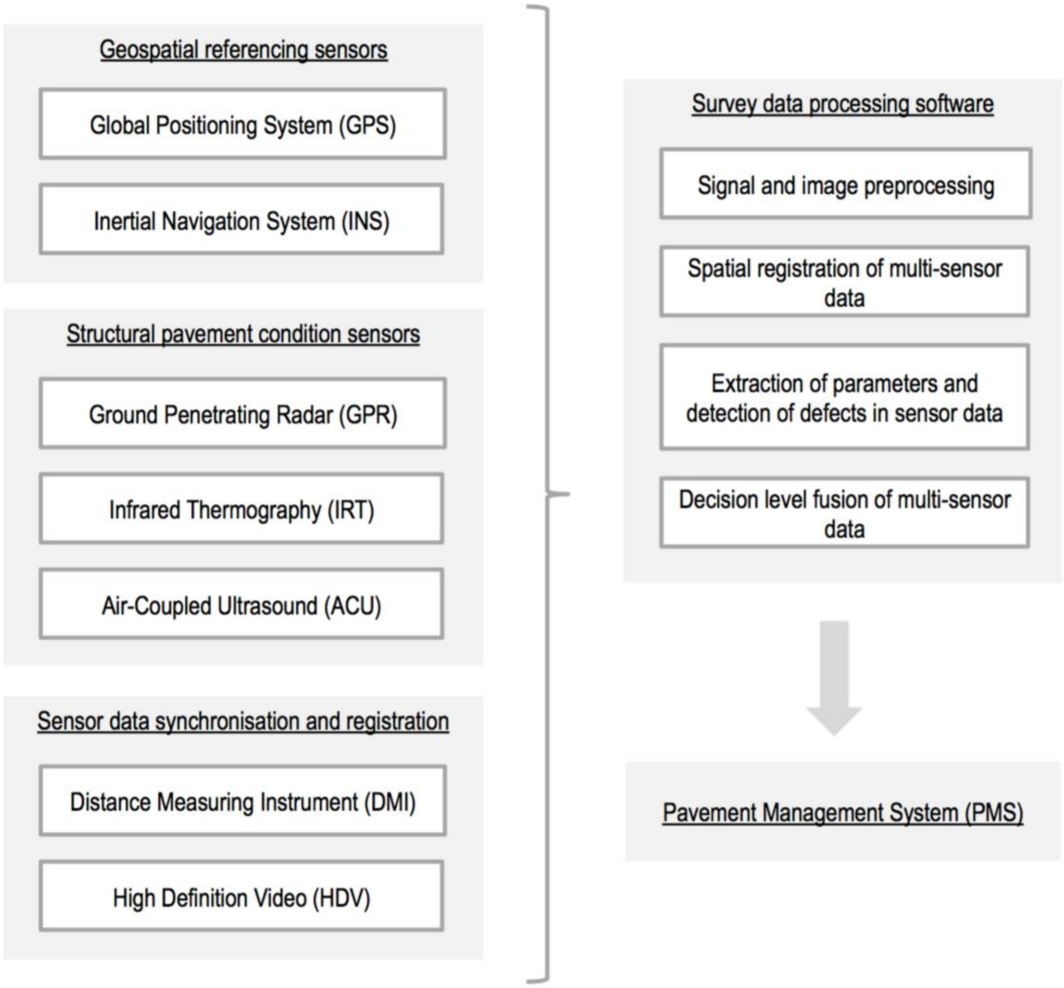

Figure 4. Design of the RPB HealTec system for pavement structural condition survey

The integrated RPB HealTec NDT system also includes the global positioning system (GPS) and inertial navigation system (INS) for accurate geospatial referencing of the survey data and distance measurement instrument (DMI) for synchronisation of the sensor data acquisition process. The GIS mapping of the detected “damage indicators” along with the HDV road lane recording are the essential inputs for decision support and maintenance planning in pavement management systems (Figure 3). Another essential aspect of the proposed RPB HealTec solution is the ability of the system to operate at traffic speeds thus optimising the road pavement survey procedure and eliminating possible traffic disruptions. The data processing software module is used for preprocessing and spatial registration the sensor data followed by the extraction and monitoring of pavement structure features for detection of surface and subsurface defects and deterioration areas. This can be further used for the rating of the defect severity and extent and assessment of the general road quality condition.

Figure 5 illustrates an example of raw NDT sensor data including the GPR and ACU B-scans of the pavement layer structure, the IRT and HDV frames of the road surface, and the corresponding GPS/INS references. In accordance with the proposed spatial positioning of the sensors, HDV and IRT camera holders are mounted on the roof of the survey vehicle in order to maximize the field of view, while the ACU transducers and GPR antennas are placed on a trolley, which is specifically designed to ensure the maximum signal penetration depth for optimal inspection of all road pavement layers.

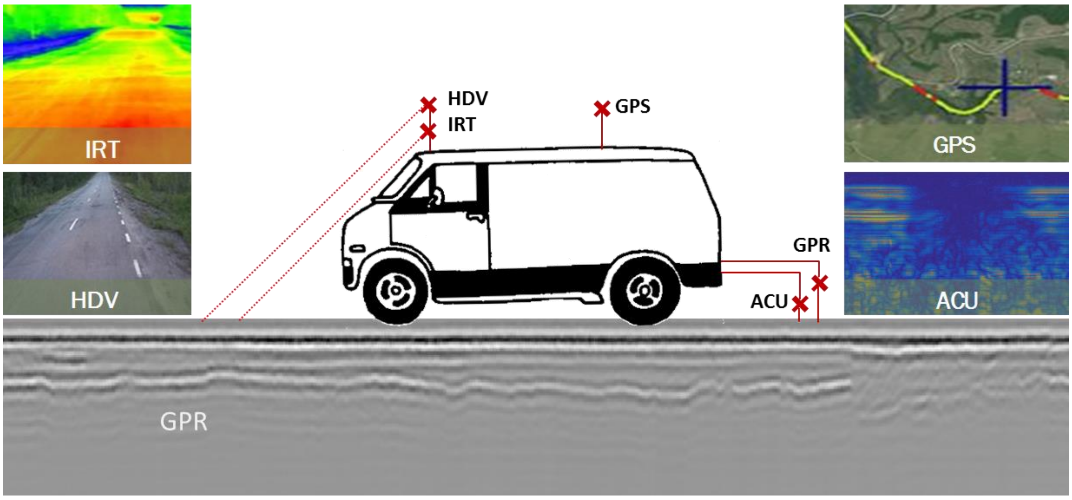

Figure 5. RPB HealTec system: NDT sensor data examples

Multidimensional sensor fusion is based on spatial registration and synchronisation of the collected data based on the navigation system outputs (i.e., GPS, INS, and DMI). Following the initial preprocessing of raw sensor data and extraction of the features and parameters corresponding to “healthy” and “distressed” pavement conditions, the defects, deterioration areas and artefacts are detected and classified. Registration of the sensor data in space from a reference point of the GPS receiver is predefined for mapping of the detected defects on the 2D reconstructed road surface. The processed sensor outputs are fused on the decision level in order to correlate the detected surface and subsurface defects with respect to their presence, severity and extent. At the final stage, the product of sensor data fusion is presented in the specific visual format as a decision-support output for the operator for diagnosis of the pavement condition of the inspected road section.

Following the acquisition of the GPR, ACU, IRT and HVD data, the general objective of the data processing is to increase the quality of signal and image information content for further feature extraction and classification for detection of detects and characterisation of the pavement structural condition. Irrespective of the sensor data type, the corresponding sequence of applied processing methods includes (Figure 6): (i) preprocessing for noise suppression and feature enhancement and restoration; (ii) segmentation; (iii) extraction of features corresponding to the presence of defects or deterioration areas, artefacts, and “healthy pavement” condition; (iv) pattern recognition based on the data analysis with respect to the feature properties such as shape, texture, magnitude, etc.; (v) parameter characterisation based on feature trend analysis and classification.

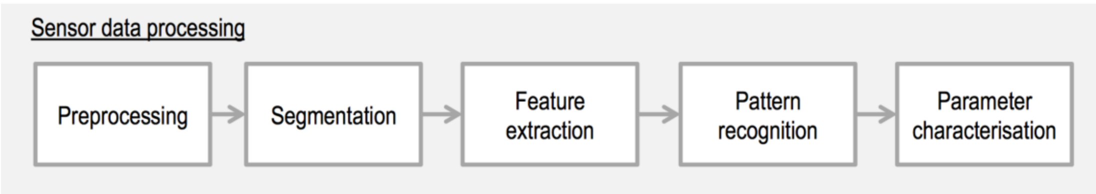

Figure 6. RPB HealTec system: NDT sensor data processing

Traditionally, 2D GRP data are processed in the time-domain based on detection of pavement layer trajectory profiles and identification of changes and discontinuities related to the variations in pavement structure or the presence of defects and deterioration areas

(Saarenketo & Scullion, 2000). The corresponding pre-processing methods include background removal, zero-offset correction, frequency and wavelet filtering, etc. The time-to-depth conversion and adaptive level thresholding are employed for extraction and tracking of the layer thickness profile information required for structural condition inventory (Leng & Al-Qadi, 2014; Varela-González et al., 2014). Diffraction hyperbola detection methods are employed for identification of defects and structure mapping (Sandmeier geophysical research, 2015). While being similar to GRP, the processing of 2D ACU data mainly focuses on the improvement of low signal-to-noise ratio associated with the losses due to high acoustic impedance mismatch. It generally includes band-pass filtering, normalisation, background subtraction for preprocessing (Krause et al., 2009) and the Fourier and Wavelet transforms for feature extraction (Berriman et al., 2006). The continuous time-domain analysis is based on the reflection level tracking and adaptive thresholding for detection of structural changes related to the surface and subsurface defects. The general preprocessing methods for HDV and IRT video data are similar and include (Furness et al., 2007): filtering, morphological operations, histogram equalisation, contrast and edge enhancement, etc., as well as the image compression in order to reduce computational and storage costs. One of the major issues in the automated video processing is related to non-uniform lighting (shadows) and external objects interfering with the road surface image. Some of the common solutions include the subdivision of a road segment into fixed size sub-windows and using local intensity values as average together with thresholding and Hough Transform for removal of external background and lane markings (Furness et al., 2007). The choice of the optimal segmentation and feature extraction methods for distinguishing between the "healthy" and "distressed" pavement surface areas depends on the defect types. The approaches for detection of cracking defects generally employ edge detection, line tracking and region growing, while potholes are detected using thresholding, morphological thinning operations and shape analysis (Koch & Brilakis, 2011). Texture intensity variations and shape analysis are used for identification of patching and changes in pavement construction as well as rutting or bleeding. Further classification and rating of the detected defects is based on the feature parameter analysis (Armenakis et al., 2012) such as shape, dimensions, direction, etc. In addition, the processing of IRT data for detection of variations in pavement segregation caused by subsurface deteriorations is based on the texture intensity analysis.

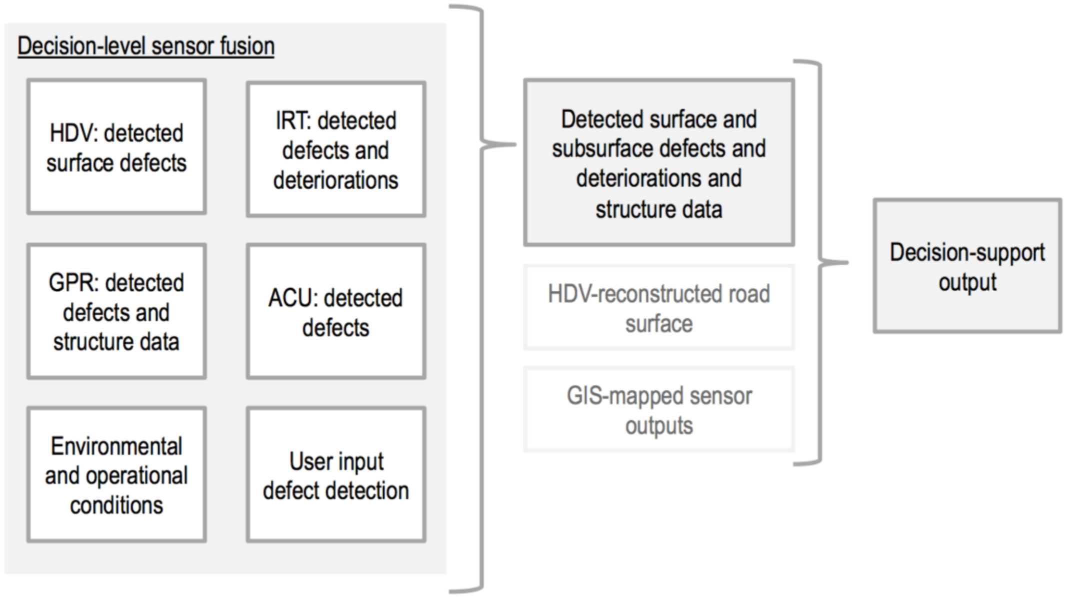

Figure 7. RPB HealTec system: NDT sensor fusion solution

In summary, the automation of the NDT sensor data analysis for the pavement condition characterisation remains one of the most complex tasks due to the common variations in pavement structure and detect features as well as a number of external factors affecting the image and signal quality. With respect to the assessment of the defect severity and extent, the characteristics of surface defects can be approximated based on the established rating guidelines (VDOT, 2012). However, due to the general lack of the automated analysis standards, the assessment of the subsurface defects requires either an operator-specific manual interpretation input or the use of trend-tracking based analysis, which grades the detected deteriorations based on the degree of deviation from the marked “healthy pavement” segments. The latter method was chosen as the optimal strategy for the automated GPR, ACU and IRT subsurface data processing.

Following the recognition of the presence or absence of the “damage indicators” such as defects, deterioration areas or artefacts, the fusion of the multidimensional sensor outputs is performed on the on the decision level with such methods as Kalman filter and Baeysian networks (Durrant-Whyte, 2008). It also incorporates the additional information on the operational and environmental survey conditions (e.g., cloudy conditions are optimal for IRT survey) as well as the presence of artefacts for the “level of confidence” weighting in order to lower the number of potential false detections (Figure 7). Based on the different spatial coverage of the sensors, the aligned GPR and ACU outputs are fused for detection of subsurface defects in the surface layer. The IRT and HDV outputs are fused frame-by-frame in order to improve IRT resolution in detection of surface defects. Since the GPR and ACU sensor coverage is limited only to the certain road lane regions, fusion of the IRT output with the GPR and ACU data is performed in local regions, which are covered by the GPR antennas. Consequently, this makes the precision of the sensor positioning with respect to each other being essential for the sensor fusion accuracy. As mentioned above, taking into account the complexity of the problem domain and routine variations in the pavement structure properties, the proposed decision-support approach is based on the “sensor alarm concept”, which maps and reports the detected “damage indicators” with respect to degree of deviation (severity) from the defined “normal state” and their spatial extent. This solution leaves the final decision to the operator, thus balancing the level of automation versus the amount of required manual user input in order to ensure the reliability of the inspection outputs.

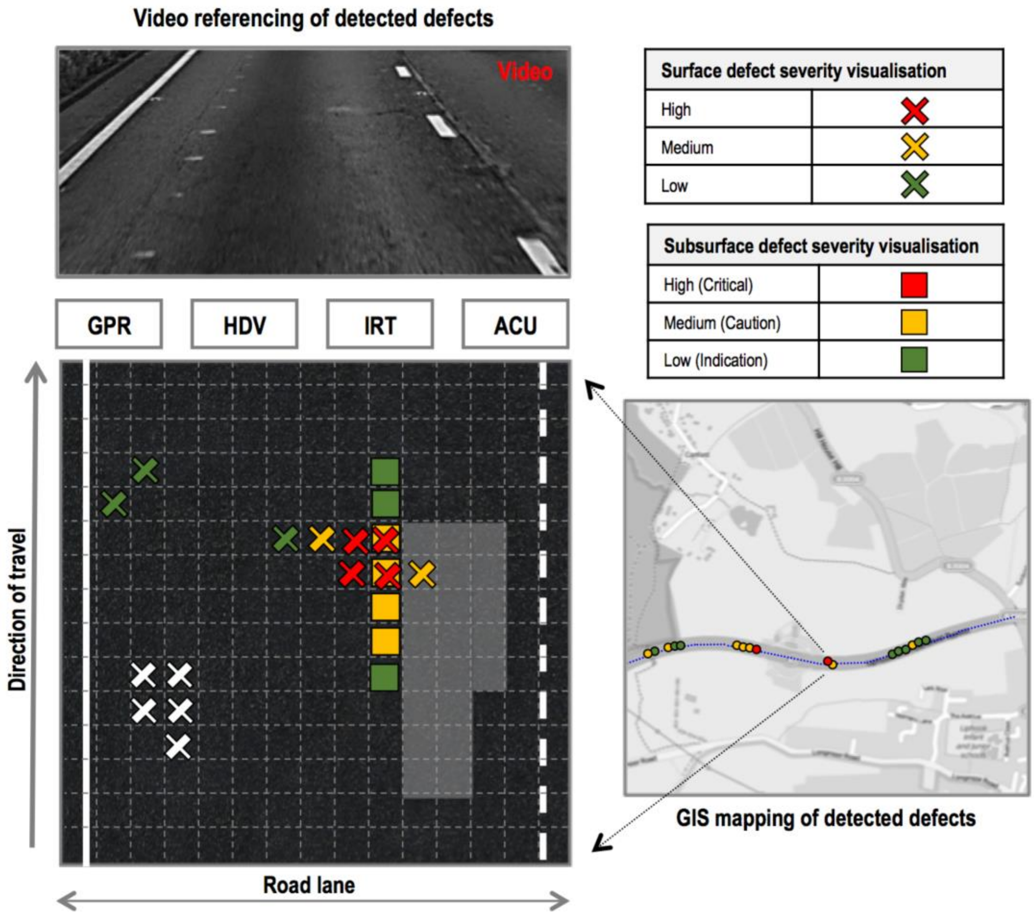

Figure 8. RPB HealTec system: decision-support output

The proposed strategy for visual representation of the resulting decision-support output is presented in Figure 8. The inspected road pavement surface is extracted from the HDV output and rectified in order to avoid interference with external sources such as passing vehicles. The extracted road lane surface is divided into segments with the processed sensor fusion outputs being correspondingly mapped to each of the segments. The detected surface and subsurface defects are depicted as "×" and "■", accordingly, with the marker colour representing the estimated severity (e.g., red represents critical defects). The defects or artefacts, which remained unclassified, are visualised as white. Since the coverage of the IRT camera for the assessment of the subsurface deterioration is wider than the GPR and ACU outputs but at the same time requires the input from the other two sensors for confirmation of the diagnosis, the unverified IRT-detected deterioration areas (deviations in segregation) are plotted in light grey. The performed survey path is visualised on the GIS map together with the locations of the detected defects. In addition, as shown in Figure 7, the RPB HealTec solution has an option for the user input for marking of the defects and deteriorations during the data acquisition or processing, thus increasing the information content of the sensor data for the semi-automatic analysis.

The reliability of the proposed solution for the sensor fusion directly depends on the efficiency of the employed sensor data processing methods consequently requiring extensive validation studies, which is especially relevant taking into account the novelty of application of IRT and ACU in road pavement inspection. In addition, the proposed sensor fusion configuration can be potentially extended with other sensors providing information on the pavement condition, such as laser profilometers.

4. Conclusions

In conclusion, following the overview of the current road pavement inspection practices this paper presented the proposed novel approach for fusion of multiple NDT sensors for structural pavement condition surveys. At the present stage of the RPB HealTec project timeline, after the formalisation of the design and preliminary implementation of the integrated NDT sensor system hardware and software, further development plan includes the following: (i) optimisation of the signal and image processing solutions for the raw sensor data streams based on the field testing results in order to enhance the defect features and lower the influence of artefacts and environmental factors; (ii) finalisation of the knowledge-based system for feature extraction and parameter characterisation based on the trend analysis and pattern-recognition techniques for the automated distress recognition and classification and identification of pavement structure changes; (iii) implementation of the optimal sensor fusion methodology with the integrated "confidence" weighing option; (iv) final implementation of the decision-support solution and GUI tool for classification, mapping, and visualisation of detected pavement "damage indicators".

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