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RESOLUTION OF MULTIPLE CONCEALED THREAT OBJECTS USING ELECTROMAGNETIC PULSE INDUCTION

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Abstract—The detection and identification of conducting objects using electromagnetic pulses to excite circulating eddy currents within the object is demonstrated by numerical simulation using a finite element time domain electromagnetic solver. The ability to discriminate between objects is based on the decay rate of the induced currents in the object, typically $\sim 100\,\mu\text{S}$. The decay rates are different for a wide variety of everyday objects, allowing threat objects such as handguns, grenades and knives to be discriminated from benign objects such as mobile phones handsets, watches, keys, etc.. Crucially, the time constant characterising an object depends only upon the electrical properties of the object (conductivity) and the shape and size of the object; the orientation of the object is irrelevant. This aspect independence of temporal current decay rate forms the basis of a potential object detection and identification system. By application of an algorithm based on the generalized pencil of function method, the authors demonstrate the ability to effectively count and indentify multiple objects carried in close proximity providing that the objects do not have very similar time constants and that signal to noise ratio is high.

1. INTRODUCTION

Pulse Induction techniques for the detection and identification of metallic objects have been reported and studied as a possible method for concealed weapon detection [1–7], both on the human body and in carried baggage. Electromagnetic Pulse Induction (EMI) relies on a generating a rapidly changing, spatially uniform magnetic field

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which penetrates and encompasses the concealed metallic object. The temporally changing magnetic field induces transient eddy currents [8–13] in the conducting object which then decay by dissipative (resistive) losses. These eddy currents decay exponentially with time and have a characteristic time constant which depends only upon the size and shape of the object and the materials from which it is made; the orientation of the object does not influence the time constant [14–20]. This aspect independence which forms the basis of a simple object identification system: a library of time constants, measured *a-priori*, can be compared with the measured time constant of an unknown sample to assess the presence or absence of a particular object or objects of interest. EMI for concealed object detection has one important advantage over resonant electromagnetic aspect independent phenomena: that is the human body has a very much smaller perturbing effect in EMI than at the microwave frequencies (~ 0.4–$2\,\mathrm{GHz}$) required for excitation of natural resonances of typical concealed threat objects such as handguns and knives [21–27]. At microwave frequencies the human body is opaque and scatters and reflects microwave energy very effectively [28], undermining the ability to extract clean and uncluttered signatures from concealed objects [24–26]. EMI operates at much lower frequencies $\sim 10\,\mathrm{KHz}$, where the human body is nearly transparent, does not support appreciable eddy currents and is therefore 'invisible' [19]. In the case where excitation occurs at frequencies where the electromagnetic wavelength is comparable with the concealed object size (Mie scattering regime), resonant effects give a second aspect independent parameter: resonant frequency and decay time. However, because EMI operates at large electromagnetic wavelengths when compared to object size, the concealed object is electrically small, and there is no resonant condition and consequently there is only one aspect independent parameter. EMI is at a disadvantage here as mapping an object in complex frequency space (two independent parameters) provides a less degenerate and more robust identifier than is possible with a single, aspect independent parameter [29].

2. THEORETICAL BASIS

There is published work in the field of EMI for a variety of uses, concealed weapons detection [1–7]; non destructive testing [30–32] ground penetrating radar for unexploded ordnance detection [18] and mining [17]. These applications rely on the same phenomena and share a common theoretical underpinning. The time domain dependence of the induced voltage on the secondary, receiver coil can be expressed as [1],

$$V(t) = \delta(t) - \sum_n A_n \exp\left(-\frac{t}{\tau_n}\right) \tag{1}$$

where A_n and τ_n are the amplitudes and time constants, respectively, of the nth eddy current mode circulating in the object. In general, an analytic solution giving the values of A_n and τ_n is not possible for all, but a few very simple cases where symmetry allows for an analytical expression. A conducting sphere is one such case [13, 16]. For a sphere of radius R; conductivity σ and relative permeability μ, the time constants τ_n are given by,

$$\tau_n = \frac{\mu\mu_0\sigma R^2}{\chi_n^2} \tag{2}$$

where χ_n are the solutions of the equation,

$$\tan(\chi_n) = \frac{(\mu - 1)\chi_n}{\mu - 1 + \chi_n^2} \tag{3}$$

The time dependence given by Equation (1) simplifies further for times which are long, when compared to the time constants of the higher ($n \geq 2$) order modes. For example the higher order modes of a sphere possess shorter time constants than the fundamental, see Equation (2), and it is assumed that this is true for other, more complex, objects. In this late time regime, after the excitation pulse or the switching off of the current in the primary coil that provides the spatially uniform magnetic field, the voltage induced in the secondary coil is simply

$$V(t) \sim A \exp\left(-\frac{t}{\tau_1}\right) \tag{4}$$

Thus we may identify an object by its aspect independent, fundamental time constant which is dependent only upon the shape, size and material that form the object.

When M multiple objects are present within the magnetic field the detected signal, again for times which are long compared to high order modes, will simply be the superposition of the signals for the objects individually,

$$V(t) \sim \sum_{n=1}^{M} A_n \exp\left(-\frac{t}{\tau_n}\right) \tag{5}$$

3. OBJECT COUNTING AND IDENTIFICATION

A pre-requisite of a security screening system based on EMI is the capability to detect and classify multiple objects that may be within close proximity to one another. As an example, a person could quite conceivably be carrying a handgun in a briefcase, a knife in their pocket and may well also have a mobile phone and other benign objects on their person. A robust and effective EMI based system is required to detect, count and identify these objects whatever their separations. Without doubt, the most serious problem posed by application of aspect independent EMI techniques is that of a single parameter being used to identify a concealed object, the fundamental time constant. There is an inherent degeneracy in this approach which may well prevent certain objects that share similar time constants being counted as individual items and therefore discriminated from one another. As can be seen from Equation (2), an object's time constant may be matched by an appropriately sized sphere. To ascertain whether this problem is significant enough to seriously limit the effectiveness of an EMI system requires the measurement or simulation of a very wide variety of objects, both threat and non-threat, which may be encountered. In this study the authors present a representative study of six commonly carried objects: A wristwatch, key and mobile phone handset as representative of benign objects and a knife, handgun and hand grenade as representative of threat objects.

Non-linear recursive fitting algorithms are not particularly suitable for the extraction of multiple time constants from a decaying temporal signal of the form of Equation (5). The fitting is sensitive to the starting points and is slow and computer intensive. The greatest problem is counting the number of objects present, as this is generally unknown *a-priori* and applying a model with an increasing number of fit parameters, terms and starting points quickly results in an unwieldy and unreliable method. The authors have investigated the application of the Generalised Pencil Of Function (GPOF) method [33, 34], which is a far more suitable and rapid algorithm for the intended application as it is a generalised eigen value problem and therefore does not need multiple iterations to arrive at a solution. This approach is suggested by Geng and Baum [19] for the extraction of time constants from non resonant objects. The GPOF algorithm decomposes the signal into a discrete set of complex frequency components; in the case of an exponentially decaying signal of the form of Equation (5), only the real parts of the complex frequency are non-zero and the imaginary (oscillatory) frequencies are ignored. The number of objects M is unknown but can be estimated, in the absence of degeneracy of time constants, by iteratively increasing the model order (the number of complex frequencies expected) of the GPOF algorithm until any new complex frequencies found have amplitude which is lower than a preset threshold value. See Figure 1. Comparison of the time constants thus

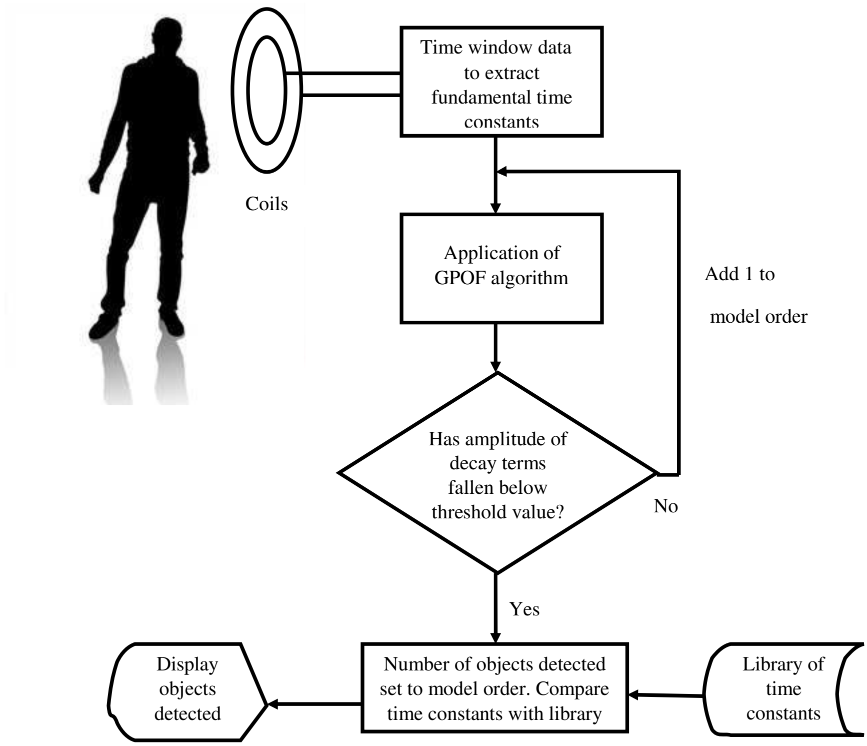

Figure 1. Flowchart depicting the processing steps and application of the GPOF algorithm to extract multiple time constants from the receiver coil time data.

obtained can then be made with a library of time constants for common or expected objects and a list of likely carried objects may then be formed. Output may be an autonomous alarm or informing the user, by screen, that a person is carrying only benign objects or that a person is likely carrying a threat object or objects.

The simulated transient data were windowed by selecting the temporal data 100 µS after the current driving the magnetic field is turned off. This is done to weight the fundamental resonance of the object. If this is not done spurious detections can arise, as higher order time constants can have sufficient amplitude to confuse the system, meaning a single object could be counted as two or more objects and the higher order time constants possibly mistakenly identified as being the fundamental time constants of other objects which are not actually present. 100 µS was chosen as this is the longest time constant of the limited objects simulated, with the exception of the hand grenade which has an unusually long time constant. However this choice of waiting 100 μS is a somewhat arbitrary choice as the exact start of the late time is dependent on the object; for spheres the start of the late time region is given as the period of the fundamental time constant [13] and for handgun sized objects as $\sim 100\,\mu$S [6]. A threshold discriminator of 5% of the maximum amplitude is applied to the amplitudes extracted using GPOF, below this value the associated time constant is not recorded.

4. SIMULATION

Numerical simulation is carried out using the commercially available finite element, time domain, electromagnetic solver software from *Vector Fields*. A large, circular coil is suitable for the purpose of generating a spatially uniform field over distances that are commensurate to typical concealed weapon sizes (~ 20 cm).

The model was validated by simulation of stainless steel spheres of conductivity $1.1 \times 10^6\,\mathrm{sm}^{-1}$ and of different radii. The fundamental time constants from the simulations were compared to Equation (2), and the simulated results agree well with theory, see Table 1.

The influence of the separation of two spheres (radii 4 and 6 cm) where simulated at varying separations, see Table 2 and both time fundamental time constants where accurately recovered irrespective of the separation between the two spheres. This important as it suggests that multiple objects can be detected and identified by means of their time constants even when they are located close together, for example when carried in a bag, providing they are not in direct electrical contact.

Table 1. Comparison of theoretical and simulated recovered time constants for stainless steel spheres of different radii.

Radius — cm	Time Constant μS (simulation)	Time Constant μS (theory)
3.0	121	126
4.0	221	224
5.0	350	350
6.0	507	504

Table 2. Influence of object separation on two stainless steel spheres (radii 4 and 6 cm respectively). The separation indicated between objects is for their closest surfaces and there is no electrical contact for the zero separation case.

Objects separation — cm	Time Constant one — µS	Time Constant two — µS
100	221	526
50	215	529
25	220	527
0.2	223	526
0.0	222	527

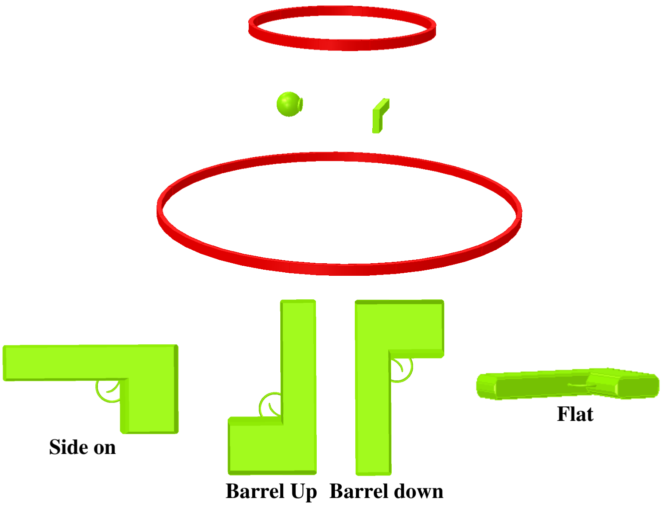

Figure 2. Examples of simulations of a handgun and hand grenade in the space between the drive (larger coil) and receiver (smaller coil) and some orientations of handgun used to validate the aspect independent nature of an object's time constant — see Table 3.

5. RESULTS

The aspect independence of the time constant of objects is the central and key effect on which the potential of EMI for concealed threat screening rests. A handgun was simulated in four different orientations (see Figure 2) and the fundamental time constant recovered in the absence of noise, there is little variation between the aspects, see

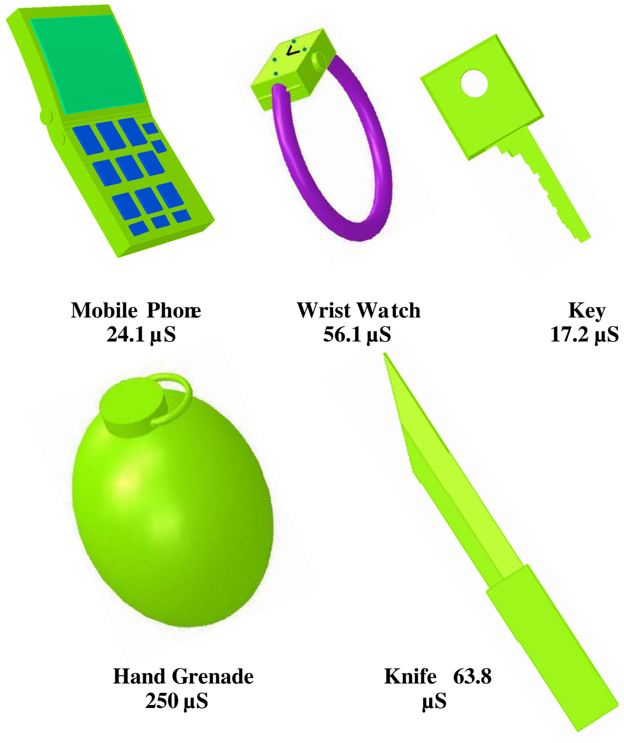

Figure 3. Five of the six items and their fundamental time constants as measured when the object is simulated individually without noise; the handgun is shown in Figure 2 and has a fundamental time constant of 72.4 µS. See Table 4 for grouped objects results. All objects are stainless steel.

Table 3. Influence of object orientation.

Material	Object & orientation		Time Constant µS
Stainless steel	Handgun	Side on	72.4
		Barrel up	72.1
		Barrel down	72.0
		Flat	73.6

Table 3. Similar aspect independence is reproduced for the other simulated objects listed in Table 4.

Six objects were simulated in a single aspect, three benign objects and three threat objects, see Figure 2 and Figure 3. These were

Table 4. Groups of two to five objects and the fundamental time constants obtained from these groupings; comparison is made to the time constants obtained for the Individual objects in the presence of different signal to noise ratios (SNR).

Objects	SNR	Hand grenade 250 µS	Handgun 72.4 µS	Knife 63.8 µS	Wrist watch 51.6 µS	Mobile phone 24.1 µS	Key 17.2 µS
Hand grenade & handgun	∞	250	74.7	-	-	-	-
	100	245	34.05[1]	-	-	-	-
	50	240	14.52[1]	-	-	-	-
	10	224[1]	-	-	-	-	-
Wrist watch & key	∞	-	-	-	53.9	-	12.4[1]
	100	-	-	-	44.2[1]	-	-
	50	-	-	-	46.6	-	-
	10	-	-	-	51.3	-	-
Hand grenade, handgun & wrist watch	∞	253	86.0[1]	-	52.0	-	
	100	238	64.4[1]	-	-	-	-
	50	215[1]	59.06[1]	-	-	-	-
	10	202[1]	-	-	-	-	-
Hand grenade, handgun, wrist watch & knife	∞	252	77.4	79.5[1]	43.0[1]	-	-
	100	236	27.6[1]	-	-	-	-
	50	210[1]	39[1]	-	-	-	-
	10	204[1]	-	-	-	-	-
Hand grenade, handgun, wrist watch, knife & mobile phone	∞	250	75.1	65.5	53.6	20.9[1]	-
	100	232	74.8	-	-	-	-
	50	226	43.6[1]	-	-	-	-
	10	231	32.5[1]	-	-	-	-
Hand grenade, handgun, knife, mobile phone & key	∞	232	69.1	65.6	-	25.1	9.25[1]
	100	222[1]	54.2[1]	33.5[1]	-	-	-
	50	221[1]	30.6[1]	-	-	-	-
	10	212[1]	26.6[1]	-	-	-	-

[1] Results with a greater than 10% discrepancy to the individually measured time constants

simulated individually and their characteristic time constants obtained, in the absence of noise, by the process described in Figure 1.

The time constants for these objects are presented in Table 4 along with the retrieved time constants for groups composed of different numbers of the six simulated objects. The time constants are retrieved under noise free conditions (SNR of ∞) and with different levels of Gaussian noise applied (SNR of 100, 50 and 10). The hand grenade has by far the longest time constant, which is related to its near spherical and smooth shape giving rise to relatively long lived eddy current distributions. Application of the simple algorithm described to the simulations of multiple objects, in the absence of noise, comprising combinations of the six objects listed in Table 4, successfully retrieves the fundamental time constants of the individual objects reasonably accurately. There is some discrepancy of time constants, notably in groups that contain more objects. The key seems to pose the greatest problem, the fundamental time constant is not accurately estimated when it is included in a group of other objects (See Table 4). The inaccuracy is probably due to the small size of the key relative to the other objects; the small size giving a much shorter fundamental time constant and a weaker contribution to the signal compared to the other, larger, objects. This results in the signals from the larger objects dominating and a greater inaccuracy in the retrieved time constant. However this interpretation seems to be incompatible with the data obtained for two spheres in proximity; see Table 2, where the larger sphere's time constant is less accurately determined than the smaller.

When noise is added to the signal at a relatively low level (SNR of 100), the identification of multiple objects is significantly impaired, with only the largest and dominant objects being counted and the smaller objects either missing or their time constants considerably corrupted to the extent that identification would not be possible. For example, in the case where the handgun, hand grenade and wristwatch are presented together, only the handgun and hand grenade are counted for an SNR of 100; the wristwatch is absent. As the SNR increases the situation worsens, for an SNR of 10, using the same example scenario, only one object is counted (the hand grenade) and the time constant is highly corrupted ($\sim$20% different from accepted value). With five items present the addition of noise prevents the smaller objects from being counted and corrupts the time constants so that identification is not feasible, in fact only the hand grenade, which has a large cross section and long time constant, seems to remain detectable and identifiable.

6. SUMMARY

The simulations demonstrate the feasibility of being able to detect, count and identify a range of commonly carried objects and also a range of weapons. However, this capability is lost if the signal is noisy and under these conditions smaller objects are not detected and aspect independent time constants are significantly corrupted, rendering identification unlikely. SNR must be better than 100 if the proposed technique is to have reasonable chance of success. If SNR can be kept suitably low then discrimination of weapons from benign objects is feasible, at least for the objects simulated, as the fundamental time constants are sufficiently distinct. The presence of multiple objects within the sensor range does not prevent counting and identification, although the accuracy of the determination of the individual objects' fundamental time constants is made worse increasing number of objects. The reason for this worsening of performance is undoubtedly due to the interaction (scattering) of the magnetic fields from the objects, i.e., the eddy currents flowing in one object give rise to a changing magnetic field which induces eddy currents in neighbouring objects and therefore blurs the time constants. In the absence of noise, the distortion of time constants when multiple objects are present is not so strong as to prevent the counting and identification of five objects from one another, with the possible exception of the key, see Table 4. Smaller objects such as a key or coins are more difficult to identify due to their smaller cross section when compared to objects such as a handgun, hand grenade or knife. This is not expected to constitute a serious problem as most threat objects are significantly larger than a key or a coin. This investigation is now being extended to the laboratory, where a demonstrator system is now being built, and it is anticipated that this work will enhance the capability of current screening procedures.

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