

Design Enhancements of the Smart Sediment Particle for Riverbed Transport Monitoring

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Abstract—This paper discusses new enhancements that are being made to the existing ‘Smart Sediment Particle’. The smart sediment particle has been designed and implemented to track its own 3-dimensional trajectory when placed in a riverbed. This device serves as a tool to detect sedimentation in rivers. The device has been developed over the years, with its size diminishing significantly down to a sphere of 2cm radius. The readings obtained from the pebble are accurate and match well with other independent motion sensor readings. Currently a novel IPT (Inductive Power Transfer) based power supply is being integrated to this device, to charge it wirelessly, when it has been extracted from the water. A new low power, miniaturized microcontroller has been introduced to minimize the power consumption and the PCB real estate of the device. The paper discusses these new enhancements in detail and also other potential enhancements such as error compensation and wireless data transfer.

Index Terms—Environmental Monitoring, Inertial Navigation, Sensors, Inductive Power Transfer

I. INTRODUCTION

Commonly available, low cost Commercial Off-The-Shelf (COTS) sensors such as accelerometers and gyroscopes can be utilized to create an autonomously operable unit to track its self-trajectory. The ‘Smart Sediment Particle’ is a collection of such sensors together with an energy source and additional circuitry, packaged into a miniaturized device, which is capable of tracing its own three dimensional trajectory in order to monitor riverbed environments [1], [2], [3]. The device is equipped with a microcontroller for data processing and storing data for later retrieval. Since the system is designed to operate for short periods of time the processor resources are sufficient to manage simple calculations and keep common offset and gain errors under control. The device is currently being redesigned with a new microprocessor and a power supply unit for more efficient operation. This paper will discuss the operational techniques of the device and the current changes being carried out to improve its efficiency and user friendliness.



Fig. 1: Smart Particle among real pebbles in hydraulic environment

This system can be easily adapted to monitor any hydraulic environment, such as a milk vat sensor. Fig. 1 depicts the smart particle in a hydraulic environment among natural pebbles.

II. BACKGROUND AND MOTIVATION

Sand and gravel particles in a riverbed are generally stationary, but with high river flow and turbulence these particles tend to be in constant motion. With changes in river flow, the initial pick-up motion of these particles, also known as ‘entrainment’, is an interesting analysis from a civil engineering perspective. The key interest is to identify the specific river flow patterns as to when the entrainment process is initialized. The ultimate goal was to create a device to studying river flow patterns and neighbouring particle forces on typical sand and gravel particles, in order to identify sedimentation in rivers. The ‘Smart Sediment Particle’ [1], [2], [3] (also referred to as the Smart Pebble) is capable of monitoring its own motion during changes in river flow, under the influence of neighbouring sediment particles, to determine causes of sedimentation in rivers. As illustrated in Fig. 2, in a laboratory environment, the smart particle is placed among similar fixed particles with miniature load cells capable of measuring inter-particle forces between the smart particle and similar fixed particles. The motion measurements from the smart particle, measured inter-particle forces and flow turbulence are used to develop a conceptual model of the entrainment process, in an attempt to understand the sedimentation process in rivers [2].

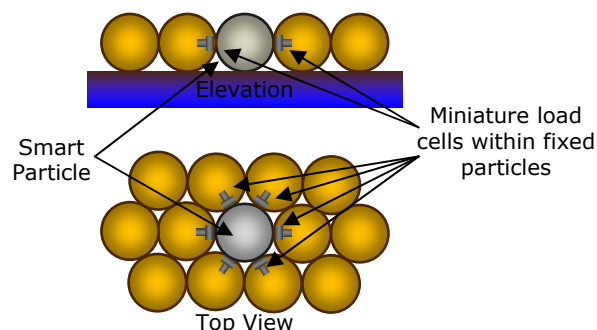


Fig. 2: Simulation of entrainment process

With motivation from the Department of Civil and Environmental Engineering at the University of Auckland, developments began a few years ago. When the development commenced the essential key features were the small physical dimensions, under water operability, unobtrusiveness to the natural process, specific gravity close to that of natural pebbles and self contained natured with an in-house energy source, memory etc [2]. Initial prototypes of the device extended on to large multiple circuit boards but over the years its size diminished until it was brought down to fit within a sphere with 2 cm radius.

III. IMPLEMENTATION

A. Initial Hardware Design

The smart sediment particle has been implemented as a complete Inertial Navigation System (INS) [4] with motion sensors, a microprocessor, external memory and an energy source. Two ADXL202 dual axis accelerometers have been utilized to measure the acceleration of the particle in each of the 3 dimensions. Three ADXRS150 yaw rate gyroscopes have been embedded to measure the rate of rotation of the pebble about each axis. The sensor measurements are read into the Microchip PIC microprocessor at regular intervals and stored in the external memory for later retrieval. All this has been fitted into a sphere of 2cm radius to meet the requirements.

Once the pebble completes the data collection process, it is extracted from the water and the data is retrieved to a PC using a serial connection. The data is processed on MatLab, using the Euler Angle method [5], Directional Cosine matrices [4] and simple integration, which will be discussed later. Fig. 3 depicts the completed implementation of the smart sediment particle.

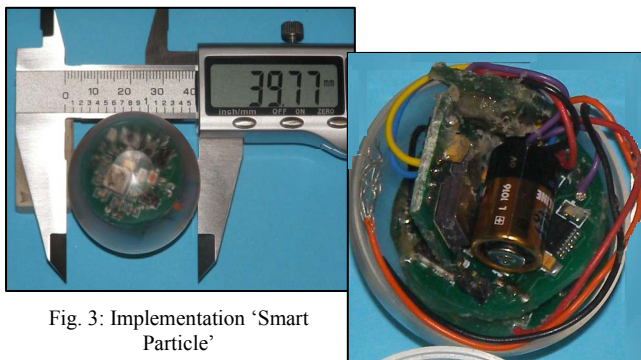


Fig. 3: Implementation 'Smart Particle'

B. Design Limitations

With the last implementation a simple 6V battery powered the device for approximately 15-20 minutes. Changing the batteries caused many inconveniences. Opening the pebble to replace batteries eventually harmed the waterproofing of the device. Replacing batteries frequently also turned out to be costly and inconvenient where measurement acquisition was concerned.

During the initial design phase energy efficiency was not given much focus as the initial concern was the proof of concept and miniaturization of the device. However, energy

conservation and minimizing consumption become important enhancement requirements at the next stage.

Extracting the data is currently done over a serial connection, which requires the particle to be opened frequently. A wireless data extraction technique would be much more feasible. However, the challenge is to devise a wireless transfer technique which would work effectively under submerged conditions, without a very high power requirement.

C. Improved Design

The design is currently undergoing few major changes including a new power supply design and a new microcontroller. A Silicon Labs C8051F931 microprocessor has been introduced to lower the power consumption of the circuitry significantly. This new microcontroller works with a supply voltage as low as 0.9V and has all the essential features required for this project [6]. The micro-miniaturized packaging of 4x4mm, will also contribute towards further reduction of PCB real estate. Currently developments are underway to replace the previous PIC18F8520 microcontroller which consumes more power and has a larger package size of 12x12mm.

The most critical microcontroller feature required for this design is the Analog-to-Digital Converter (ADC). The C8051F931 has a 10-bit successive-approximation-register (SAR) ADC. There is also an autonomous low power burst mode which automatically enables the ADC, captures and accumulates samples and then puts the ADC in a low power shutdown mode without the CPU intervening [6]. This is an added advantage when it comes to power conservation in the circuitry. The 16-bit accumulator is capable of automatically over-sampling and averaging the ADC data [6]. The single ADC in the microcontroller is capable of multiplexing up to 23 input channels, with the inbuilt analog multiplexer [6]. The 6 different sensor readings are included to form a single set of measurements. Since the ADC does not require the ADC inputs to be connected to specific pins, they are simply connected to standard I/O pins of the processor and multiplexed into the ADC when required, without any additional components being required.

With the microcontroller operating on a voltage as low as 1.8V, the reference source of the ADC is vital. The reference voltage can be either external or one of two internal reference voltages. The gain settings can be set to either x1 or x0.5. With the x1 mode a full scale reading is determined by the reference voltage and the x0.5 mode allows a full scale reading to go as high as twice the reference voltage [6]. To ensure low power operation the supply voltage is being maintained at the typical value of 1.2V which keeps the ADC reference voltage also at the same value. Therefore the maximum ADC reading possible is as low as 2.4V. With the ADC reference voltage dropping down significantly, certain design changes are being made to adapt the motion sensors to this situation. Precision voltage dividers are used to make sensor outputs compatible with the processor. Upon completion of the new design the power requirement is expected to reduce significantly.

The previous design of the smart particle used a single 6V alkaline battery as its power source. The new version uses a completely new power supply design based on super capacitors and Inductive Power Transfer (IPT) technology, which is currently being implemented.

An IPT based rechargeable power supply is also being introduced in the new design. IPT allows contact less power transfer, with magnetic fields directly linking energy to where required [7]. IPT is immune to dirt, dust, water, ice and chemicals and is licensed to industrial clean rooms and factory automation systems internationally by The University of Auckland's commercial arm, Auckland UniServices Limited [7].

An IPT system magnetically couples primary and secondary components. The primary component is a power supply with a power converter and a loop or track coil carrying high frequency (10 – 100 kHz) and high magnitude (10-300A) alternating current. The secondary component is a movable pick-up with a pickup coil and power conditioning. An inductive electromotive force is induced in the pick-up coil and the power conditioner regulates power as required. [8]

The external primary side of the circuit will host a primary coil and a power converter. An alternating current is produced by the power converter while runs through the primary coil, which in turn produces an alternating magnetic field. The secondary pick-up coil, which will be housed within the pebble, is magnetically coupled with the primary coil. The magnetic field in the primary coil induces a voltage in the secondary pick-up. Since the gap between the primary and the secondary side is slightly larger than that of a transformer, the induced voltage would not be sufficient to drive the rest of the circuitry. Therefore a power conditioner is required to boost the voltage and regulate it. [9] It is important maintain a compact nature on pick-up side of the circuit so that the pebbles dimensions will not need to be increased.

The power picked up by the pickup circuitry will charge the rechargeable cell. However the battery will simply be a backup power source while an array of super capacitors will be the primary energy source. The power picked up over the IPT system will charge these super capacitors which are as large as 10F. Since super capacitors alone cannot be used as an energy source due to their fast energy release, but together with a battery can serve as a ‘hybrid battery’ [10]. Many advantages can be experience when using super capacitors, such as, longer life-time due to high number of charge-discharge cycles, extremely low internal resistance, high efficiency (up to 97-98%), high output power, extremely low operating temperature and therefore low heating levels, smaller size, rapid charging using simple charge techniques and improved safety also be placed to store the excess energy [11],[12],[13].

This new rechargeable IPT power supply addresses the problem of having to replace batteries and also the frequent opening of the article. Therefore the waterproofing will remain intact and the cost of batteries will be eliminated. It is important to miniaturize this part of the circuitry as much as possible so that the pebble will not need to be expanded. Fig. 4 outlines the basic pickup and primary track outline for the smart particle.

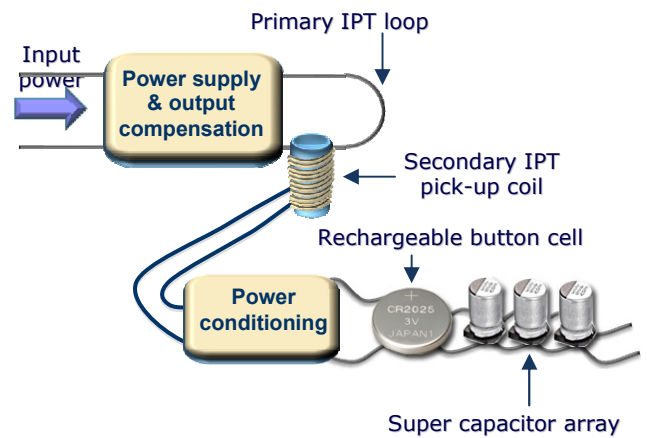


Fig. 4: IPT power supply design for smart particle

Since the pebble is not transparent and also spherical, precise alignment between the pickup and the track cannot be achieved. Therefore a 3 dimensional flux field will ensure efficient power transfer. Multiple primary tracks, fixed in three orthogonal directions will need to be driven accordingly to produce this alternating flux. Fig. 5 illustrates the typical orientation and setup of primary coils to form a 3 dimensional power supply. The three switches S_1 , S_2 and S_3 are alternately turned on for one third of the total period. Therefore a magnetic field is alternately generated in each of the coils for one third of the period [9].

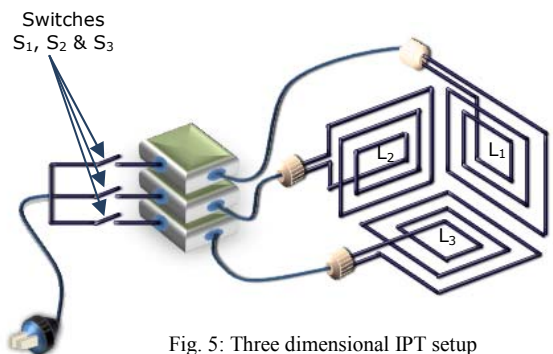


Fig. 5: Three dimensional IPT setup

The primary track for the charging unit will be housed within a ‘charging container’ with 3 dimensional power zone. Fig. 6 illustrates the IPT charging setup of the smart particle.

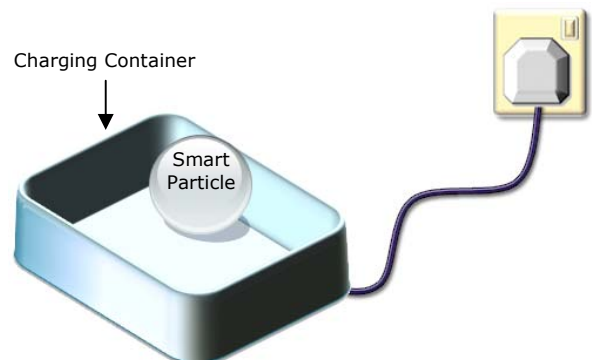


Fig. 6: IPT charging setup for smart particle

In addition to these design improvements, another vital requirement is a wireless data transfer system. Although currently this is not in the system yet, it will be added in the near future. A possible option is to transfer the data to a surface level buoy and then use standard wireless communication technologies to transfer the data from that point onwards.

IV. CALCULATIONS

Once the data stored on the pebble has been downloaded on to a PC some complex mathematical processing is done to extract the actual trajectory of the particle. The processing is based on basic strap-down INS theories and calculations, given that the initial position of the particle is known. Fig. 7 simplifies the mathematical process into a flow diagram.

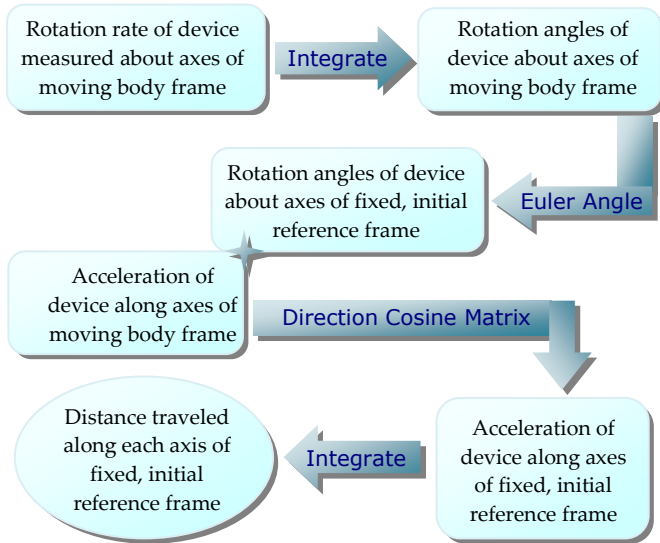


Fig. 7: Mathematical flow of obtaining the distance traveled along each axis

The sensors are fixed to form a three dimensional ‘body frame’ where sensor measurements will be taken with respect to and this body frame is in constant motion when the pebble moves. The final calculations will reveal the motion parameters with respect to the initial orientation of this body frame, which will be considered the fixed reference frame. To obtain this, there are many axis conversion techniques such as Euler Angle, Direction Cosine and Quaternion [4]. Based on its simplicity and applicability for small rotation angles, the Euler angle technique was chosen for this application [5]. The transformation is performed by taking three successive rotations about three orthogonal axes in turn [6]. Angular rotations about z, y and x axes are taken as ψ , θ and ϕ . Fig. 8 depicts the alignment of the orthogonal axes, and the positive rotation direction about each axis.

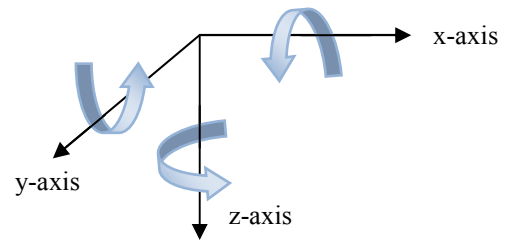


Fig. 8: Orthogonal Axes and Positive Rotation Direction about Each Axis

If ω_z , ω_y and ω_x are gyrations about each axis respectively as measured by the gyroscopes, each rotation angle about the body frame can be worked out as,

$$\psi = \int \omega_z dt \quad \theta = \int \omega_y dt \quad \phi = \int \omega_x dt$$

With positive rotations about each axis three cosine matrices can be obtained as C_1 , C_2 and C_3 . Assume that the first rotation of the body frame occurred about the z axis and this produces the matrix C_1 ,

$$C_1 = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This changes the orientation of the entire body frame. The rotation about the new y axis produces C_2 .

$$C_2 = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & \cos \theta & 0 \end{bmatrix}$$

The rotation about the new x axis produces C_3 .

$$C_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix}$$

The transformation from reference to body frame is given by the product of these three matrices which is the rotation matrix,

$$C_n^b = C_3 \cdot C_2 \cdot C_1$$

The inverse of this transformation, the body to reference frame transformation is given by the direction cosine matrix,

$$C_b^n = C_n^{bT} = C_1^T \cdot C_2^T \cdot C_3^T$$

The assumption $\sin x \rightarrow x$ and $\cos x \rightarrow 1$ can be made as the rotation angles are small, considering the relatively fast sampling and slow angular rotations. Thus by ignoring products of angles which become infinitesimally small, the above equation can be simplified to a skew symmetric form as,

$$C_b^n = \begin{bmatrix} 1 & -\psi & \theta \\ \psi & 1 & -\phi \\ -\theta & \phi & 1 \end{bmatrix}$$

Multiplying the body frame by the transpose of the rotation matrix produces the conversion of any vector from the body frame to the reference frame.

$$r^n = C_b^n \cdot r^b$$

Since COTS accelerometers and gyroscopes are used for this system, r^b can be indicated as below. A_{x-b} , A_{y-b} and A_{z-b} are the accelerations of the body frame along the corresponding axes, as measured by the accelerometers.

$$r^b = \begin{pmatrix} A_{x-b} \\ A_{y-b} \\ A_{z-b} \end{pmatrix}$$

This gives a simplified expression for r^n as, which will produce the accelerations with respect to the reference frame.

$$r^n = \begin{pmatrix} 1 & -\psi & \theta \\ \psi & 1 & -\phi \\ -\theta & \phi & 1 \end{pmatrix} \begin{pmatrix} A_{x-b} \\ A_{y-b} \\ A_{z-b} \end{pmatrix}$$

In the previous design, this final equation was implemented in MatLab to devise the particles motion with respect to the reference frame. With the new implementation the mathematical components are being integrated into the microprocessor for higher efficiency and user friendliness.

V. PERFORMANCE

A set of readings from the last design of the smart particle has been outlined in Fig. 9 as a proof of successful operation. The graph outlines the acceleration of the pebble along a single axis, after the mathematical processing. Plotted alongside this is the accelerations of the shake table on which the pebble was placed when these measurements were obtained. The shake table accelerations were measured independently through inbuilt accelerometers.

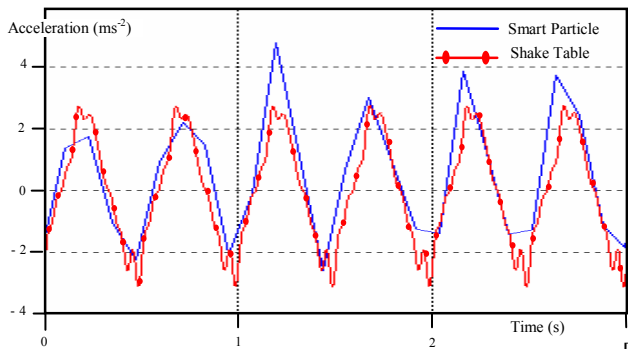


Fig. 9: One Dimensional Acceleration of Smart Particle and Shake Table

It must be noted that the shake table accelerations are purely based on accelerometer readings and no gyration data, which would cause them to be less accurate as opposed to those of the smart particle. The smart particle was placed within a tightly fitting cube when this test was performed and there is allowance for it to move within the cube, while the cube follows the acceleration of the shake table.

Additionally there are some factors which lead to minor errors in the measurements. The most significant among these is the cumulative errors of the sensors. A slight error in the sensor measurements would be multiplied twice at the point the

trajectory of the particle is plotted due to the double integration. Therefore accurate sensor readings are vital for this purpose.

A. Error Sources and Error Compensation

Digitization of analog data at ADC interfaces can lead to quantization errors. If the quantization interval is q the quantization error can be simplified down as below [9], [3].

$$\text{Quantization Error} = \frac{q}{2\sqrt{3}}$$

With the new microcontroller with its 10-bit ADC and a reference voltage of 2.4V, q works out to be 0.0023V, which creates an rms quantization error of 0.00068V. Though this may seem insignificant for a single measurement the cumulative error over time and due to integration could be a significant error.

The correct sampling frequency can also help eliminate undesired amplitude errors [14], [15]. The time domain amplitude error between the sampled signal and the real signal is directly proportional to the ratio between signal amplitude and range of the ADC. Therefore by increasing the ADC range can reduce the amplitude error.

The direction cosine matrix calculated previously is infact an estimation based on small angles. Therefore the direction cosine matrix, which is relied upon to perform the axis transformation is not completely accurate and thus can create cumulative errors in the long run. In the calculation phase, assuming that $\sin x \rightarrow x$ and $\cos x \rightarrow 1$ also lead to errors. However it is a tradeoff between accuracy and faster processing and a compromise needs to be made. These error surces and compensation techniques have been discussed extensively in Ref. 3.

Integrating error compensation techniques into the data processing stage is also a focus of this research. Estimates of sensor biases, scale factor errors and sensitive axis misalignments can be determined with the aid of certain calibration tests [4]. By performing a certain number of 'Six position' and 'Static rate' tests a single value can be calculated to model these errors and be integrated as a correction factor when the data is being processed. Detailed discussions of these tests are available in Ref. 3 and 4.

VI. FUTURE DEVELOPMENTS

While the discussed developments are in progress there are some other key development areas that need to be looked into. One main focus should be the development of a wireless data transfer system. Initially a wireless technique can be devised to retrieve the data when it is extracted from the water. This can eliminate the need to open the pebble to extract data. With both the wireless rechargeable power supply and wireless data transfer available, the water proofing of the device can be left intact.

A main hurdle to overcome is transmitting data while the pebble is in water. Since wireless technologies that work in submerged conditions require high power and bulky circuitry,

achieving this with the current dimension limit is very challenging. However, using a floating buoy at water surface level with a data collection portal attached to the pebble will significantly reduce the power requirement for data transfer, because the transfer distance is significantly smaller. And from the point of the buoy onwards, standard wireless communication techniques, such as a GSM network, can be used.

VII. CONCLUSIONS

It can be concluded that the smart sediment particle has successfully achieved its goal of tracking its self trajectory. The data extracted from the pebble has produced accurate readings and served as an excellent proof of concept. Currently a novel, IPT based power supply design is underway to charge the pebble wirelessly when it is extracted from the water. The wireless charging system includes two parts, a 3-dimensional charging container and a miniaturised pickup circuit. Additionally as a measure to minimise the power consumption of the device a new SiLabs microcontroller has been introduced. This processor works with a supply voltage as low as 0.9V and typically requires 1.2V for operation. The miniaturised package and the low voltage operation of this processor makes it highly feasible for this project. Integrating error compensation factors at the data processing level is also an objective of this research. A major potential development is to develop a wireless data transfer technique, which would completely eliminate the need to open the pebble.

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