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# Low frequency sensitive tiltmeters for dynamic structural status evaluation of hystorical monuments

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***Abstract –*** **The dynamic structural analysis of historical monuments for health evaluation and long term preservation requires a long term acquisition of linear and angular displacements, mainly in the low frequency region ($\ll 1\,Hz$), that has to face to many technical problems spanning from the problem of uncoupling displacements from tilts, to cost and size of instrumentation. To overcome this problem, we developed an innovative small and light linear and angular sensor, based on the Folded Pendulum Model, perfectly suitable for a permanent non-invasive low-power monitoring of historical monuments. In this paper, after a description of the tiltmeter model and performances, we focus the attention to its application to historical monuments monitoring.**

## I. INTRODUCTION

In the last years the interest has largely increased in linear and angular high sensitivity large band low frequency ($< 1\,Hz$) sensors for compliance tests and long term monitoring of large buildings and infrastructures (dams, bridges, sky-scrapes) in connection with site natural events (subsidence, micro-seismicity or earthquakes), information necessary to understand the global behavior of the structure in connection with the sites, aimed to the evaluation of their health status and to reduce the risks for the population.

This transversal approach is based on a very simple idea. In fact, each structure, of any material and size, has its own intrinsic dynamics, defined by a set of vibrations modes dependent on the geometry and on the materials: the vibration modes of a structure are its *fingerprint* directly connected with its geometrical and physical characteristics. For example, a structural compliance test is aimed to check the compliance of the design and measured vibration modes: deviations among the design and measured vibration modes of a structure indicate an implementation not coherent with its design. In a similar way, the evolution of the modal structure underlines a dynamical evolution that may lead to partial or total structural collapses (e.g. weakened or broken beams), as well as the appearance of additional vibration modes, that can be correlated with the dynamical evolution of the site. A careful analysis, in synergy with FEM (Finite Elements Method) simulations may quantify these structural features highlighting structural failures at a very early stage (e.g. cracks), which need more detailed and local investigations to understand the causes (degradation of materials, structural misalignment, earthquakes effects, etc.) to drive very specific and successful actions to remove their causes. Furthermore, not less important, and probably often neglected due to the lack of the necessary instrumentation, is the long term monitoring both of the angular and torsional internal motions of the structures such as the subsidence of the site, due to natural events (subsidence, local micro-seismicity, earthquakes, wind, etc.) and anthropic actions (gas and oil extraction, city car traffic, etc.) that may mine stability of the structure. A complete and effective real-time and long term evaluation of the global health state of the structure in connection with the dynamical evolution of the site, is, therefore, fundamental to the identification of possible causes of damage and to the definition, well in advance, of all the actions for their prevention and safeguard, minimizing, at the same time, also the risks for the population.

The technological progress has allowed the design of different classes of high quality sensors (MEMS, NEMS, ecc.), although not able to satisfy the sensitivity requirements ($< 10^{-9}\,m/\sqrt{Hz}$) in the low ($< 1\,Hz$) and very low ($< 1\,mHz$) frequency region, a region necessary to identify the slow and very slow dynamics of the structures. Classical mechanical sensors, already applied in very different fields (industry, aerospace, engineering, geophysics, etc.), although characterized by bandwidths, extended in the low frequency regions (often as large as $10^{-2}\,Hz \div 1\,kHz$) with good sensitivities (down to $10^{-10} m/\sqrt{Hz}$), are not enough compact and often very heavy, but above all, very expensive for the implementation of distributed long-term monitoring systems for application in the field of historical monuments for health evaluation and long term preservation.

In fact, these sensors are generally based on a force feedback design, a classic control technique aimed to improve their linearity and dynamic range: the inertial force is compensated acting on the test mass with a feed-back force proportional to the ground acceleration, generally obtained with electromagnetic transducers. Although this technique is very effective, these sensors have to face not only their intrinsic limitations (e.g.thermal noise, etc.) but also limitations in sensitivity and band due both to their readout system noise (LVDT, optical lever, etc.) and to the often unpredictable noises generated by the coupling of their force feed-back actuators (e.g. magnet-coil actuators) with environmental noises. The latter sensitivity limitations do not apply to inertial sensors, being affected practically only by their readout system noise: the output signal is proportional to the test mass displacement (or to velocity) due to the inertial force generated by seismic ground motion.

One of the possible research lines, probably the most obvious, is that of improving the mechanics of the inertial sensors. The folded pendulum is a very promising mechanical architecture for the implementation of inertial sensors. Based on the Watt's Linkage (1774) [1], the horizontal folded pendulum architecture is a well known architecture, first hypothesized by Ferguson in 1962 [2], that can be modeled as a combination of a simple pendulum and of an inverted pendulum both connected to one end by means of joints to a bar (the central mass or inertial mass) and to the other ends by means of other joints to a supporting structure fixed to the ground (frame), reducing at the same time weights and sizes.

The horizontal folded pendulums, configured in force feedback, have been proven very effective as horizontal vibration isolation systems for gravitational wave detectors and low frequency accelerometers [3, 4, 5]. But, although very effective, the dimensions and the complexity of these implementations prevented a large diffusion and application, until the progress in precision micromachining and electric-discharge machining technology allowed the implementation of compact horizontal monolithic folded pendulums as linear accelerometers [6, 7] and as tiltmeters [6, 8, 9, 10]. All the implemented folded pendulum configurations are based on the same architectural typology, characterized by joints working in tension, that allow their operation only with a force feedback configuration [11, 12].

The innovative mechanical architecture introduced with the UNISA Folded Pendulum class of sensors [13, 14, 15, 16], characterized by two of the four couples of flexure joints working in compression (the inverted pendulum ones), overcome this problem, leading to a large improvement of the folded pendulum performances: the folded pendulum seismometer (no force feedback) is limited, in principle, only by the thermal noise of the mechanics and by the sensitivity of the readout system. Typical performances obtained with standard horizontal UNISA Folded Pendulums are low natural resonance frequencies (down to values of $\approx\ 60\,mHz$ obtained with a $14\,cm$ size sensor [11]), large measurement bands ($10^{-7}\,Hz\ \div\ 1\,kHz$), sensitivities (typically of the order $10^{-12}m/\sqrt{Hz}$ and $10^{-10}rad/\sqrt{Hz}$ with optimized LVDT (Linear Variable Differential Transformer)), but better with optical readout systems (e.g. laser interferometric readouts). It is worth underlining that a suitable readout system design may provide the folded pendulum with large immunity to environmental noises (e.g. optical readouts)[11, 12, 17, 18, 19].

In the following sections after a description of the linear and angular UNISA Folded Pendulum and a discussion on the mechanical performances and sensitivity of its components in connection with different mechanical and optical readout configurations [11, 17, 18], we present and discuss the results obtained and expected in a next future with monitoring system based on this class of sensors in the field of cultural heritage preservation [20, 21].

## II. FOLDED PENDULUM THEORETICAL MODEL

Despite the apparent simplicity of the folded pendulum mechanical architecture, analytical solutions of its motion equations based on a Lagrangian approach are actually very complex, so that, its dynamical behavior can be described with enough accuracy only with a numerical approach. On the other hand, an analytic approach, although not enough accurate to be used for folded pendulum designs, guarantees a global and synthetic overview of its mechanical performances and dynamic behavior. The Lagrangian two-dimensional analytical model of Bertolini [22], based on the simplified Liu et al. [3] model, generalized by Barone et al. [11], developed to describe the dynamical behavior of a horizontal folded pendulum, whose basic mechanical scheme is shown in Figure 1, is sufficient for the latter purposes.

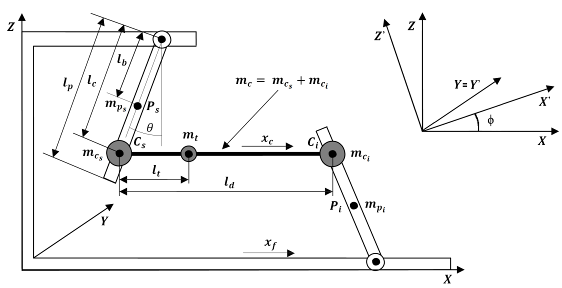


*Fig. 1. Folded Pendulum Mechanical Scheme [11].*

The simplified folded pendulum model schematically consists of two vertical arms of equal length, $l_p$, connected to one side to a single support (frame) by means of two hinges, forming a simple pendulum of mass $m_{p_s}$ and an inverted pendulum of mass $m_{p_i}$. The two pendulums masses are concentrated in their centers of mass, $P_s$ and $P_i$, respectively, positioned in $l_b\ =\ l/2$. The other sides of the arms are connected (in $C_s$ and $C_i$, respectively) to a bar of mass, $m_c$, and length, $l_d$, by means of two other hinges, while the mass of the central bar is modeled with two equivalent masses $m_{c_s}$ and $m_{c_i}$, being

$$m_c = m_{c_s} + m_{c_i} \tag{1}$$

whose value is defined by the position of the center of mass on the central bar, $l_m$ (being $l_m < l_d$), measured with respect to the pivot point, $C_s$, according to the relations

$$m_{c_s} = m_c\left(1 - \frac{l_m}{l_d}\right) \qquad m_{c_i} = m_c\left(\frac{l_m}{l_d}\right) \tag{2}$$

The positions of the couples of equivalent masses ($m_{p_s}$, $m_{p_i}$) and ($m_{c_s}$, $m_{c_i}$) differ by a constant, so that for small deflection angles, $\theta$, the centers of mass of the two arms have the same velocity, $\dot{x}_p$ and the two equivalent masses ($m_{c_s}$, $m_{c_i}$) have the same velocity of the center of mass of central bar, $\dot{x}_c$. Therefore, the Folded Pendulum can be described by the classic Lagrangian:

$$\mathcal{L} = T - U \tag{3}$$

where $T$ is the approximate analytic expression of the kinetic energy, expressed by [3]

$$\begin{aligned} T &= \frac{1}{2}\left(m_{p_s} + m_{p_i}\right)\dot{x}_p^2 + \frac{1}{2}\left(m_{g_s} + m_{g_i}\right)\dot{x}_c^2 \\ &+ \frac{1}{2}\left(J_s + J_i\right)\dot{\theta}^2 \end{aligned} \tag{4}$$

with $J_s$ and $J_i$ moments of inertia of the two arms, and where $U$ is the approximate analytic expression of the potential energy, that for the folded pendulum becomes

$$\begin{aligned} U &= \frac{1}{2}\left[m_{g_s} - m_{g_i} - 2\frac{m_g}{l_d}\frac{M_{eq} g_{eq_x}(\phi)}{K_{e_{eq}}}\right] l_c g_{eq_z}(\phi)\theta^2 \\ &+ \frac{1}{4}\left[m_{p_s} - m_{p_i}\right] l_p g_{eq_z}(\phi)\theta^2 + \frac{1}{2}k_\theta\theta^2 \end{aligned} \tag{5}$$

with $k_\theta$ global elastic constant of the joints, introduced to take into account that the pivot points may be hinges but also flexure joints, the most critical components of a folded pendulum (often $< 100\,\mu m$ thickness), each characterized by an elastic constant, $k_{\theta_j}$, so that

$$k_\theta = \sum_{j=1}^{n} k_{\theta_j} \tag{6}$$

where $n$ is their total number and whose physical behavior is well described by the generalized Tseytlin formula [23]. Assuming, then, the folded pendulum frame fixed to the ground ($x_f = x_g$) and applying the approximation of small deflection angles, $\theta$, that allow to retain only the first order terms in the Lagrangian, then the solution of the Lagrangian equation of motion (Eq. 3) shows that the Folded Pendulum dynamic behavior is equivalent to that of a spring-mass mechanical oscillator, a classical second order oscillator with natural resonance frequency, $f_o$, expressed by:

$$\begin{aligned} f_o(\phi) &= \frac{1}{2\pi}\sqrt{\frac{\left[\frac{l_p\Delta m_p}{2l_c} + \Delta m_c - \frac{2M_{eq}m_c g_{eq_x}(\phi)}{K_{e_{eq}}l_d}\right]\frac{g_{eq_z}(\phi)}{l_c} + \frac{k_\theta}{l_c^2}}{\left(m_{p_s}+m_{p_i}\right)\frac{l_p^2}{3l_c^2} + \left(m_{c_s}+m_{c_i}\right)}} \\ &= \frac{1}{2\pi}\sqrt{\frac{K_{g_{eq}}+K_{e_{eq}}}{M_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{K_{eq}}{M_{eq}}} \end{aligned}$$

where

$$\Delta m_p = m_{ps} - m_{p_i} \qquad \Delta m_c = m_{c_s} - m_{c_i}, \tag{7}$$

$K_{e_{eq}}$ is the global equivalent elastic constant of the flexures of the suspension joints, defined as

$$K_{e_{eq}} = \frac{k_\theta}{l_c^2}, \tag{8}$$

$K_{g_{eq}}(\phi)$ is the gravitational equivalent elastic constant, function of the geometrical and inertial characteristics of the folded pendulum in presence of an equivalent gravitational acceleration, defined as

$$K_{g_{eq}}(\phi) = \left[\frac{l_p\Delta m_p}{2l_c} + \Delta m_c - \frac{2M_{eq}m_c g_{eq_x}(\phi)}{K_{e_{eq}}l_d}\right]\frac{g_{eq_z}(\phi)}{l_c} \tag{9}$$

and $M_{eq}$ is the equivalent mass, defined as

$$M_{eq} = \left(m_{p_s} + m_{p_i}\right)\frac{l_p^2}{3l_c^2} + \left(m_{c_s} + m_{c_i}\right) \tag{10}$$

Eq. 7 demonstrates that the resonance frequency of the Folded Pendulum classically depends on suitable combinations of physical and geometrical parameters (masses, lengths of the rods, etc.) but it depends also on the external acceleration fields, $a_{ext_z}$, and on the rotation angle, $\phi$. As expected, for a horizontal folded pendulum ($\phi = 0^o$) and in absence of external acceleration fields ($\vec{a}_{ext} = 0$), Eq. 7 reduces to the well known expression of resonance frequency of the classical folded pendulum [11].

Although, in principle, this simplified model could be already sufficient to globally understand the peculiar features of a folded pendulum, nevertheless, an accurate and effective description of its dynamics requires the introduction of global energy losses in the model, that synthesizes in a simplified but effective way both internal (e.g. internal frictions in the joints) and external (e.g. air damping) losses [11]. The folded pendulum acceleration mechanical transfer function is then expressed as [11]

$$H_a(s) = \frac{X_c(s) - X_g(s)}{A_g(s)} = \frac{X_o(s)}{A_g(s)} = \frac{(1 - A_c)}{s^2 + \frac{\omega_o}{Q(\omega_o)}s + \omega_o^2} \tag{11}$$

where $Q(\omega_o)$ is the global mechanical quality factor, whose dependence on the resonance frequency has been theoretically predicted and experimentally demonstrated on folded pendulum prototypes[11], and where $A_c$ described the center of percussion effects [11].

Concerning the Folded pendulum behavior as angular sensors, this property arises with folded pendulum pivot points implemented with elastic flexure joints. For $\phi \neq 0^o$, then the new angular rest position of the central rod, $\theta_o \neq 0^o$, is determined by the forcing due to the component of the equivalent gravitational acceleration along the $x$-axis direction, $g_{eq_x}$, to the elastic force generated by the folded pendulum flexure joints and/or to an applied external force along the $x$ direction, $a_{ext_x}$. The angular rest position of the central mass of a folded pendulum mechanical system is solution of the following static condition

$$M_{eq} l_c g_{eq_x}(\phi) - k_\theta \theta_o = 0 \tag{12}$$

Therefore, the small deflection angles, $\theta$, present in the equation of the potential, have to be evaluated around the new static condition $\theta_o$. Again Eq. 3 is a good approximation also for slowly varying angular displacements, assuming the folded pendulum moving through states of static equilibrium. It is always possible to remove this hypothesis, extending the above model also to the case of rapidly varying angular displacements, but, although it is not limitation of principle, actually it complicates the model.

## III. THE UNISA FOLDED PENDULUM

Single-axis monolithic linear and angular UNISA folded pendulums are characterized by a very reasonable size with very low natural resonance frequencies (down to $\approx 60\,mHz$) and are generally used as seismometers or and accelerometers, with sensitivities strongly dependent on the readout system, being the sensitivity of the mechanics limited by its thermal noise [11]. In particular, the innovative application of laser interferometric techniques for the readout (Michelson interferometer) have largely improved their sensitivity in the low frequency band and increased their immunity to environmental noises [7, 11, 12, 17, 18].

In Figure 2 three different implementations of the UNISA folded pendulum for linear and angular measurements are shown. In particular, it is important to notice the new implementation of a very light ($40\,g$) UNISA Horizontal Folded Pendulum, model GI16. This sensor, shown in more detail in figure 3, is made of Aluminum Alloy 6082-T6, has dimensions ($50\,mm \times 50\,mm \times 18\,mm$), hinges characterized by ellipticity (16/5) and thickness ($100\,\mu m$) and has the same performances of the model GE15 ($78\,mm \times 80\,mm \times 40\,mm$, 250 g) in terms of resonance, frequency, bandwidth and sensitivity 2. This relevant characteristic is consequence to the important scalability property [11, 12] that characterize the folded pendulum: with a suitable combination of physical and geometrical parameters of its components it is possible to implement folded pendulum with very different weights and size, but with the same characteristics in term of transfer function, a very relevant property that allows large miniaturization of this class of sensors, of which the model GI16 is one of the first results. This relevant properties make this sensors perfectly suitable for application in the filed of cultural heritage, aimed to the preservation of monuments and building, because, being very small and light, is not at all invasive, allowing the implementation of distributed system for long term monitoring of their dynamics allowing the determination of a complete state of the system.

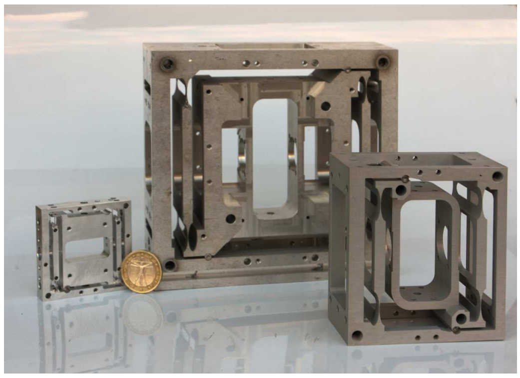

*Fig. 2. Uniaxial Folded Pendulums - model GI16 (left), model GF15 (center) and model GE15 (right).*

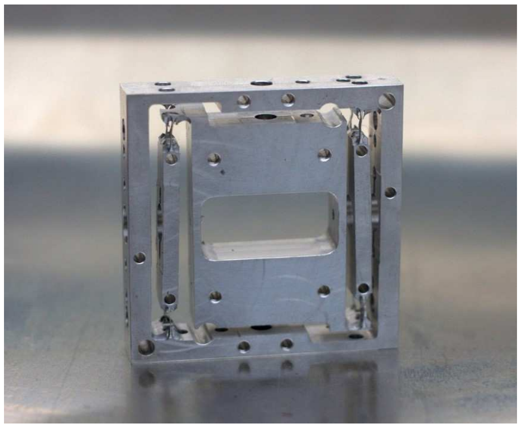

*Fig. 3. Uniaxial Folded Pendulum - model GI16.*

Figure 4 shows, as an example, typical acceleration sensitivities (at $T = 300\,K$) of the monolithic UNISA Folded Pendulums, model GE15, tuned at a resonance frequency of $3.75\,Hz$ equipped with four different readouts: commercial LVDT readout, optical lever readout with a Position Sensing Device (PSD); high sensitivity LVDT; Michelson interferometer. The sensitivity of the STS-2 by Streckeisen [24] and of the Trillium-240 by Nanometrics [25], representing the state-of-the-art of the low frequency seismic sensors, are reported for comparison, together with the Peterson New Low Noise Model

(NLNM) [26] and the McNamara and Bouland Noise Model [27], representing the minimum measured Earth noise evaluated from a collection of seismic data from several sites located around the world. Figure 4 also shows that, being the sensitivity limits of folded pendulum inertial sensors defined by their thermal noise [11], then the instrumentation sensitivity and the measurement band are practically determined by the folded pendulums resonance frequencies and by the quality of the readouts. Of course, many other configurations and techniques exist in literature suitable for the implementation of folded pendulum readouts: the choice depends on the requirements of the specific application, often based also on parameters like robustness, compactness and, last but not least, cost.

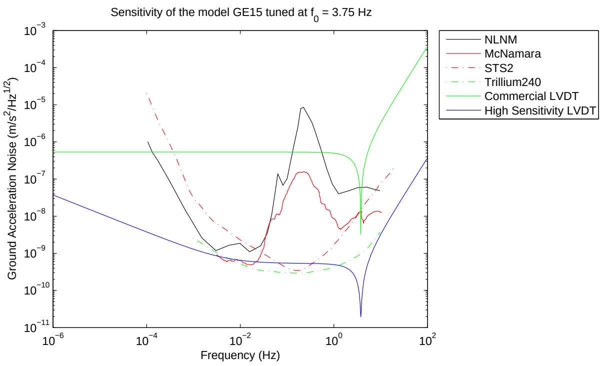


*Fig. 4. Sensitivity curves of the UNISA Folded Pendulum - model GE15 - with different readouts, tuned at a resonance frequency of $f_o = 3.75\,Hz$ [12].*

For very low frequency studies, like the one requiring a global understanding of the long-term dynamical behavior of the site on which the monument is positioned, more appropriate is the very low-frequency large-band UNISA Folded Pendulum model GF15. This sensor is made of Aluminum Alloy 7075-T6, has dimensions $140\,mm \times 134\,mm \times 40\,mm$ and flexures (hinges) of ellipticity (16/5) and thickness ($100\,\mu m$). This sensor, developed for geophysical applications, can resonate at very low natural frequency (down to 60 mHz) with external calibration masses (not shown in figure). This result is still more relevant if the small dimensions of the monolithic folded pendulum are taken into account.

Figure 5 shows the typical acceleration sensitivities (at $T = 300\,K$) of the monolithic UNISA Folded Pendulums, model GF15, tuned at a resonance frequency of $250\,mHz$ equipped again with four different readouts. Finally, Table 1 presents a global summary of some of the performances of the UNISA class of Folded Pendulums.

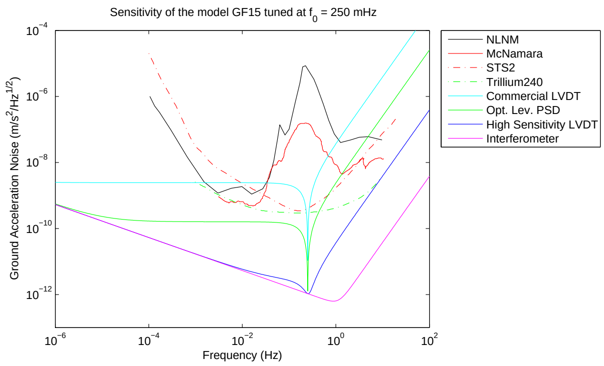


*Fig. 5. Sensitivity curves of the UNISA Folded Pendulum - model GF15 - with different readouts, tuned at a resonance frequency of $f_o = 250\,mHz$ [12].*

| **Parameter** | **Range** |
|---|---|
| Band $(Hz)$ | $10^{-7} < B < 10^{3}$ |
| Sensitivity $(m/\sqrt{Hz})$ | $10^{-15} < S_{lin} < 10^{-6}$ |
| Sensitivity $(m/\sqrt{Hz})$ | $10^{-10} < S_{ang} < 10^{-6}$ |
| Directivity | $D > 10^{4}$ |
| Res. Frequency $(Hz)$ | $5 \cdot 10^{-2} < f_o < 10^{3}$ |

*Table 1. UNISA Folded Pendulum Ranges.*

## IV. CONCLUSIONS

The present versions of the UNISA monolithic Folded Pendulum are already very good instruments for many applications, even if they have not yet reached their ultimate sensitivity and are going to be furtherly reduced in size and weight. The limitations in terms of sensitivity and band of the linear and angular UNISA Folded Pendulums [13, 14, 15] are due only to the readout system electronic noise, to the thermal noise of the mechanical joints and to the air damping, when not operated in vacuum. The application to the low frequency large band monitoring of the Trajan Arch in Benevento (Italy), performed as field test in 2015 has already demonstrated the feasibility of implementation of a monitoring system based on the UNISA Folded pendulums, showing the possibility of exploring a band, yet unexplored, necessary to understand the dynamics of the monument and to evaluate its health status [20, 21]. Long term tests with linear and angular Folded Pendulums have been already planned and/or are in course on selected historical monuments and sites to demonstrate the effectiveness of the approach described in the paper: the first results are expected by the mid of the next year.


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