Development of a low cost 3D DIC system for surface strain analysis in sheet metal forming operations

Reference No. : 182022012223

Saved By : Dr. SURESH KURRA

Saved Date : 01-May-2022

Dr. SURESH KURRA

ksuresh.iitd@gmail.com

Assistant Professor (Mechanical Engineering)

Birla Institute of Technology & Science Pilani, Hyderabad Campus

Shamirpet-keesara road, jawahar nagar, shameerpet, hyderabad, Hyderabad, Telangana-500078

Technical Details :

Scheme : Core Research Grant

Research Area : Mechanical & Manufacturing Engineering & Robotics (Engineering Sciences)

Duration : 36 Months

Contact No : +919701189052

Date of Birth : 01-Jul-1980

Nationality : INDIAN

Total Cost (INR) : 24,79,400

Is PI from National Laboratory/Research Institution ? No

Project Summary :

Digital Image Correlation (DIC) is a non-contact optical technique to measure the full-field strain over the surface of the deformed component. The basic concept of DIC is to compare two images of the component before and after the deformation. Displacements and strains are determined by correlating the position of pixel subsets in the original and deformed images based on the contrast in grey intensity levels. Due to the simplicity and versatility of the DIC method, it has been used for many applications. The current project was focused on developing a cost-effective 3D DIC System for full-field strain analysis in sheet metal forming operations. The project is executed in two phases. The first phase concentrates on static strain measurement, and the second phase focuses on dynamic strain measurement. In static strain measurement, the strain is measured by capturing the images of the formed component after complete forming. In dynamic strain measurement, the images are captured during an active forming operation, and strains can be calculated at any instant during forming operation. For static strain analysis, the flat sheet is printed with a circular grid or square grid, or mixed grid (circle and square) with edge length/diameter in the range of 2 mm to 3 mm by laser engraving or screen printing. The flat sheets are deformed to the required shape by forming operations. The deformed component with the deformed grid is placed on a rotating table, and the camera captures multiple images. The image processing techniques are used to capture the points on deformed grids to evaluate the strains. In dynamic strain measurement, a camera rig is designed with multiple cameras, and it is placed on the forming press to capture the images of the deforming component during forming operation. The captured images will be processed with a recently developed open-source 3D DIC software called Multi-DIC. Multi DIC system has been designed particularly for multi-view analysis and has been successfully used earlier to get the displacement and strains in lower limbs of humans very accurately. Therefore, the feasibility and implementation of multi DIC for full field strain analysis in sheet metal forming operations will be investigated in the project's second phase. To make the system cost effective, raspberry pi cameras will be used for image acquisition instead of expensive machine vision cameras. The accuracy of raspberry pi cameras for DIC applications has already been tested and multiple case studies were published in the recent literature. Apart from the cost, this camera can be integrated easily with python scripts and libraries for digital image processing. It is also possible to implement marker-less calibration during image acquisition with this camera system. Various camera parameters such as exposure, ISO, shutter speed, and frame rate can be controlled precisely via software with raspberry pi single-board computers (SBCs).

Objectives :

- Design and development of 3D static strain measurement system for full-field strain analysis in sheet metal forming operations using DIC principles.
- Design and development of dynamic 3D strain measurement system for full-field strain analysis in sheet metal forming operations using DIC principles.
- Testing and validation of results obtained from developed systems with commercial full-field strain measurement systems.
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Keywords :
Full-field strain analysis, DIC, Sheet metal forming, Image processing, Camera

Expected Output and Outcome of the proposal :

1. The required hardware and software is developed for static full-field strain analysis in sheet metal forming operations. 2. The required hardware is developed for dynamic full-field strain analysis in sheet metal forming and is integrated with open source 3D DIC software. 3. The developed device is calibrated, tested, and standardized against the commercial full-field strain analysis systems.

Suitability of the proposed work in major national initiatives of the Government:

Make in India

Theme of Proposed Work:

Manufacturing

Collaboration Details for last 5 Years :

Planned Collaboration for the proposed work with any foreign scientist/ institution ? No

SNo.	CO-PI Details
1	 **Srinivasa Regalla** regalla@hyderabad.bits-pilani.ac.in Professor(Mechanical Engineering) **Birla Institute of Technology & Science Pilani, Hyderabad Campus** Shamirpet-Keesara Road, Jawahar Nagar, Shameerpet, Hyderabad, TELANGANA, HYDERABAD D.O.B : 05 Aug, 1968

Other Technical Details

1. Origin of the Proposal:

Digital Image Correlation (DIC) is a full field non-contact optical technique to measure shape, motion, and deformation on almost all materials, even in extreme experimental settings. Originally DIC was developed for characterizing the material properties in experimental mechanics; DIC is widely used in different sectors. In the automotive industry DIC systems are used to characterize the new material and to determine forming limits curves for sheet metal. In the aerospace industry, DIC systems are used for basic static mechanical tests to determine material behavior, high strain rate tests, aircraft panel tests, and entire airplane strength tests. DIC systems are used for tensile, compression, and wall shear tests of a concrete platform with different steel fibers and whole building strain tests under earthquake simulations in the civil engineering industry. In Bio-Mechanics, DIC is used to study implant mechanics after implanting in the body, testing soft and hard tissues, mechanical properties of natural and synthetic biological material, and body parts.

In recent decades, substantial work has been done to improve DIC algorithms' performance and define good practices for performing experiments and calibrations. Therefore, the market for commercial DIC systems is accelerating faster. There are significant developments at the international level in automatic strain measurement using image processing techniques. GOM, ASAME Technology, FMTI systems, Correlated Solutions Inc, Dantec Dynamics, and ICASOFT are a few organizations that are commercially developing and supplying image processing-based strain measuring systems around the world.

GOM has developed ARAMIS system for dynamic 3D strain measurement and ARGUS for static 3D strain measurement. For strain measurement, the specimens are printed with circle/square grid pattern for the ARGUS system and a speckle pattern for ARAMIS. FMTI developed a portable device to measure the static strain after forming at a selected location. ASAME develops single point and full-field strain measurement systems based on image processing techniques. The company Correlated solutions has two products for automatic strain measurement called VIC-2D and VIC-3D. VIC-2D systems are used to measure in-plane displacement and strain. VIC-3D systems are used to measure the strains over the complex 3D geometries.

In china, every steel manufacturer and every automotive industry is equipped with DIC systems. In India also, there was tremendous growth in the automotive and aerospace sectors in the recent past. The Indian automotive industry is expected to reach US$ 251.4 – 282.8 billion by 2026. The Indian aerospace and defense market is projected to reach US$ 70 billion by 2030. These industries require DIC systems for material testing and characterization. There is a strong need to develop versatile, robust and accurate DIC systems indigenously to meet the requirements of different sectors such as automotive, aerospace, and biomedical in India.

2. Review of status of Research and Development in the subject

2.1 International Status

There are significant developments at the international level on automatic strain measurement using image processing based techniques. GOM, ASAME Technology, FMTI systems, Correlated Solutions Inc, Dantec Dynamics, and ICASOFT are few organizations that are commercially developing and supplying image processing based strain measuring systems around the world. Due to their cost, high-end commercial 3D-DIC systems are still inaccessible for many laboratories for small factories interested in lab testing materials.

The following section describes the applications of DIC based automatic strain measurement systems for formability analysis of sheet metal parts.

Quach et al. (2021) used the DIC system to calibrate the ductile damage model parameter from a series of uni-axial tensile tests and hydraulic bulge tests covering a wide range of stress triaxiality. Rosa-Sainz et al. (2021) used DIC System to enhance strain measurement accuracy in polymer sheets to construct forming limit curve (FLC) and fracture forming limit curve (FFLC). Song et al. (2020) used the DIC system to detect the onset of necking in sheet metal forming and compared it with different necking criteria. Zheng et al. (2020) used DIC System with laser speckles to measure the strains at elevated temperatures in thin metal sheets and thick foils. Pérez Caro et al. (2020) used DIC System to calibrate the GISSMO damage model parameters from the uniaxial tensile test of different Specimen geometries. Vitu et al. (2018) used DIC System to analyze the Strains of Zinc alloy in the hydraulic bulge and compared it with analytical models. Merklein et al. (2014) captured the Surface topography of the formed component using DIC, and the onset of localized necking is identified by the surface height difference. Huang et al. (2011) used the DIC method to evaluate anisotropic coefficients r-values (Lankford coefficients). They found that DIC provided more accurate and consistent values than manual measurement. Peterkova et al. (2016) used the DIC system to study the strain distribution in the tube flaring process. Cui et al. (2013) used DIC System to study the strain distribution in different parts (hyperbolic cone, skew cone, elliptical cone) formed by the incremental forming process. The measured strains were compared with analytical and simulation results.

Chaimongkon et al. (2021) used an Auto grid Strain measurement system to plot the forming limit diagram (FLD). The Marciniak test specimens with a Square grid were used for strain analysis. Tensile test specimens with different triaxiality ratios were also used to predict the fracture loci by the Lou-Huh fracture model. Panich et al. (2018) used the DIC system to get the fracture loci of advanced high strength steel (AHSS) sheet ineffective plastic strain - triaxiality space and maximum, minimum principal strain space. The Nakajima stretch forming and tensile tests were performed in combination with the DIC method. Rencheck et al. (2017) evaluated the FLC of the aluminum alloy at various temperatures using a time-dependent DIC method and position-dependent ISO technique. The DIC time-dependent technique was found to be more efficient without sacrificing accuracy and consistency. Min et al. (2017) used the DIC technique to obtain forming limit strains, and different methods are proposed to determine the onset of localized necking. Bagheriasl et al. (2015) performed a limiting dome height (LDH) experiment with DIC to predict the FLD of aluminum Sheets at elevated Temperatures. They found good agreement between the FLDs predicted using DIC and circle grid (CG) method. However, the degree of scattering was increased significantly in the CG methods at higher temperature tests.

2.2 National Status:

To the knowledge of PI, there is no automatic strain measurement system available with Indian make. The available automatic strain measurement systems in the country are mostly imported from other countries. However, many research groups are working in the sheet metal forming area. Most researchers adopted manual methods such as Mylar tapes, traveling microscopes, stereo microscopes, etc., to measure the limit strains in the formed part. The imported automatic strain measurement systems are available in some organizations but are expensive. The following section focuses on some of the research studies carried out by Indian researchers on strain analysis in sheet metal forming.

Velmanirajan et al. (2014) investigated the forming limits of AA8011 alloy at elevated temperatures. The major and minor strains from circle grid analysis were measured manually using traveling microscope. Sekhar et al. (2014) also used traveling microscope to measure the limit strains during the formability analysis of cryorolled Al-Mg-Si alloy. Sateesh Kumar et al. (2015) evaluated the formability of adhesively bonded sheets with different adhesives. The major and minor strains are measured in the necking zone by manual methods. Bandyopadhyay et al. (2015) constructed the stress-based FLDs to study the formability of tailor welded blanks (TWB). The strains in the critical zone are measured by manual methods. Prasad et al. (2016) studied the forming limits of Inconel 718 through circle grid analysis. The deformed grid was measured by stereo microscope for strain analysis. Kotkunde et al. (2017) developed experimental and theoretical FLDs for Ti-6Al-4V alloy under warm conditions. The limit strains for FLDs are measured using traveling microscope. Satish et al. (2017) studied the formability of AA6061 aluminum alloy in cryorolling and warm forming. The limit strains in the necking zone are measured using a stereo zoom microscope.

Baranwal et al. (2016) studied the effect of plastic anisotropy on forming behavior of AA6061 aluminum alloy sheets. The complete deformation history was measured using GOM based digital imaging system with ARAMIS software. Bhargav et al. (2015) constructed the strain-based FLDs for advanced high strength steel sheets. For this, the strains in the necking zone were measured using an online ARAMIS system, and the DIC technique did further analysis. Vadavadagi et al. (2020) constructed forming limit diagram for the low carbon steel by measuring the limiting strains using the GOM DIC system. In this system, the circular dots are initially printed and images are captured before deformation (circle) and after deformation (elliptical) to measure limiting major and minor strains. Kumar et al. (2022) investigated the incremental sheet forming process with the Lemaitre damage model. The strain variation on the specimen's surface for the damage model calibration is estimated with the help of GOM Correlate software. Ghosal et al. (2020) used in-situ 3D DIC to measure the local strains in a uni-axial tensile test to evaluate the effect of anisotropy on necking. Paul et al. (2019) used the DIC system to measure in-plane strains in tensile and notched specimens to construct FLDs.

The literature review shows that most of the researchers used manual methods for strain measurement in sheet forming. For last five to six years, some researchers have been using imported DIC based automatic strain measurement systems. However, such imported devices are very expensive. This indicates a strong need to develop a cost-effective strain measurement system. Such systems are beneficial to industries, research organizations, and academic institutes.

2.3 Importance of the proposed project in the context of current status

DIC technique has been widely used in automotive, aerospace, civil, and bio-medical sectors. The non-contact, full-field, and large deformation characteristics of DIC systems attracted many sectors for shape and deformation analysis. The literature review on strain analysis in sheet metal forming shows that most of the researchers in India used manual methods for strain measurement. These methods are time consuming and less accurate compared to automatic strain measurement. However, the automatic strain measurement systems are not manufactured by any Indian firm, and most of these systems are imported from other countries. This imported equipment is very expensive. There is a strong need to develop low-cost automatic strain measurement systems in India to meet the requirements of industries and research organizations.

The recent initiatives by the Government of India, such as Make in India and Atma Nirbhar Bharat, are accelerating Automotive, Aerospace, and bio-medical sectors in India. These sectors require DIC based systems for material testing and characterization; in many countries, DIC systems are used in these sectors. There is a need to equip these industries with more versatile, accurate, and robust DIC systems developed indigenously.

The current project aims to develop the full field static and dynamic strain measurement system for sheet metal forming applications. The unique features of these systems are given below

- Commercial 3D static strain measurement systems support only circular grids. We develop the software which can handle different grid patterns in Python (circular, square, and mixed).
- A Commercial 3D static strain measurement system uses a single camera; in the current project the hardware is designed with single and multiple cameras.
- The current commercial dynamic 3D strain measurement softwares are not tailored for multi-view analysis. In the current project, open source multi-view software called Multi DIC is tailored for dynamic full-field strain analysis in sheet metal forming.
- Many researchers have been using raspberry pi cameras to build the hardware for different DIC applications in the recent past. In the current project also raspberry pi cameras will be used to minimize the cost of the system.
- Last but not least, it is possible to save the foreign exchange by developing these systems indigenously. Moreover, the knowledge gained through this project helps to develop DIC systems for other applications indigenously.

2.4 If the project is location specific, basis for selection of location be highlighted

Not applicable.

3. Work Plan

3.1 Methodology

In the current project, two approaches are proposed to get the full field strain distribution in sheet metal forming operations using DIC (i) 3D static strain measurement system (ii) Dynamic 3D strain measurement system.

For the 3D static strain measurement system, the flat sheet is printed with different grids (circular, square and mixed grids) and then deformed into the required shape in the press. The images of the formed component are captured at different angles by keeping it on a rotary table. The images are processed using developed software in Python. A typical schematic of the proposed 3D static strain measurement system and different grid patterns is shown in the following Fig. 1

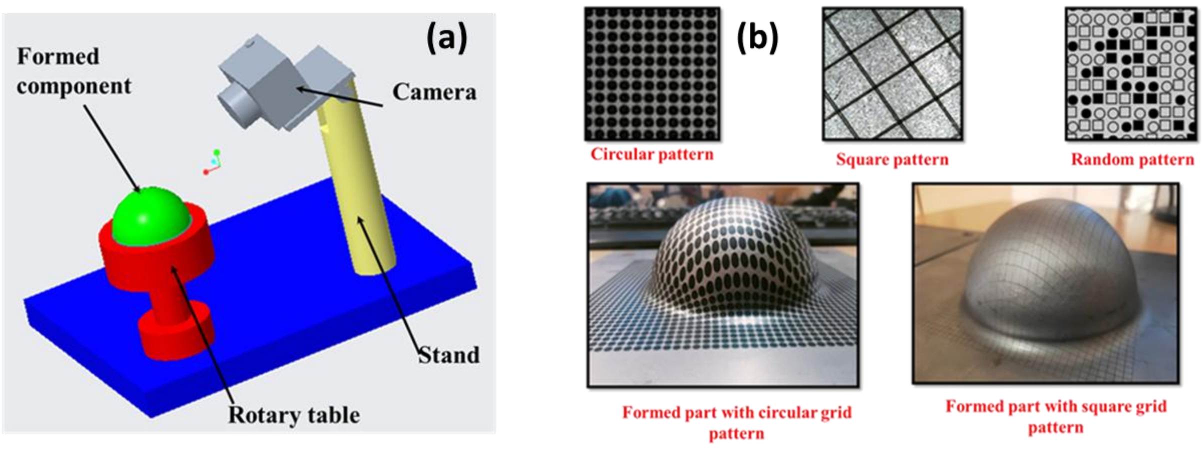

Fig.1 The schematic of (a) proposed 3D static strain measurement system (b) different types of grids used for strain analysis

For dynamic strain measurement, a flat sheet is printed with a speckle pattern and deformed into required shape on the press. A camera test rig is placed on the forming press, which captures the video of the forming process. The video will be converted into images and processed using open source software Multi DIC for getting full-field strain distribution. A schematic of the proposed dynamic 3D strain measurement system is shown in the following Fig. 2

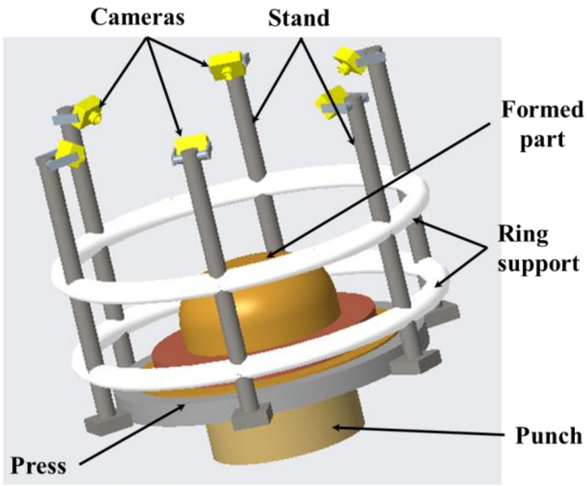

Fig. 2 Schematic of proposed 3D dynamic strain measurement system

The following flow chart (Fig. 3) shows different steps in estimating the 3D strain on the formed component. Each step is also discussed in brief.

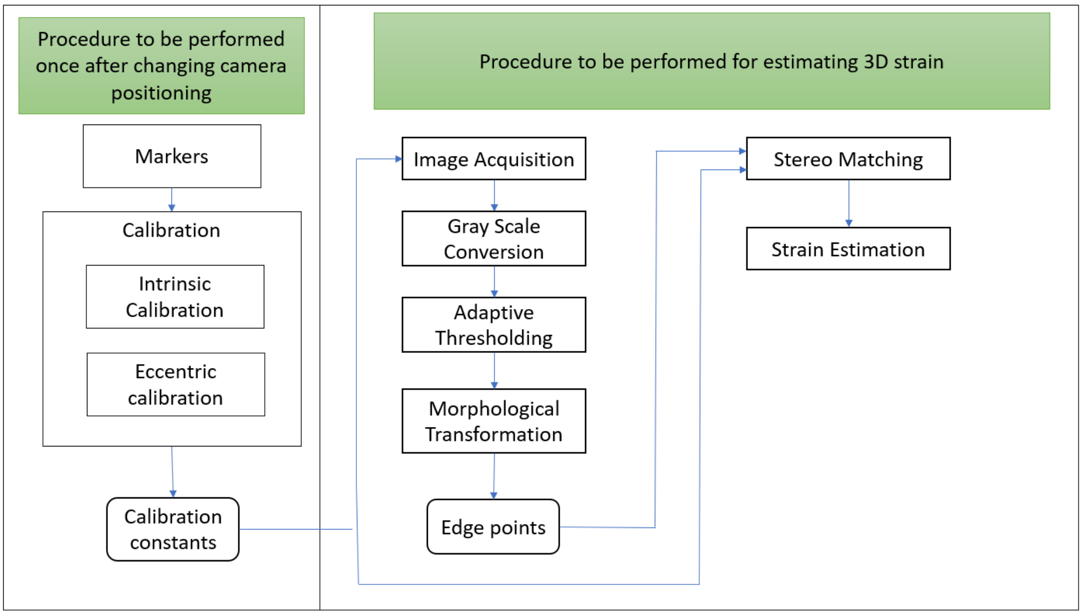

Fig. 3 Different steps in camera calibration and 3D strain measurement

Procedure to be performed once after changing camera positioning

The following procedures are followed whenever there is a change in camera placement or if one or more cameras are replaced. This process can be time taking, and performing it once would be sufficient.

1. Markers

Marker placement is a crucial stage in camera calibration. Markers are objects with the known dimension and can be easily segmented from the given image. The marker coordinate frame is considered a world frame for our reference. A typical marker with the world coordinate is shown in Fig. 4(a).

2. Calibration

Calibration is a process of estimating camera parameters (both intrinsic and eccentric) using the known dimensions of a marker or object Fig. 4(b).

The world coordinate frame is estimated from the marker. The transformation matrix which transforms Point P from world coordinate frame to image coordinates is referred to as the projection matrix and is given by

$$\begin{bmatrix} \grave{u} \\ \grave{v} \\ \grave{w} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ zw \\ 1 \end{bmatrix} \qquad (1)$$

Here $X_w = [x_w, y_w, z_w]$ are the coordinates of point P with respect to the world frame. The Projection matrix (P_m) contains both intrinsic and eccentric parameters.

Eccentric Parameters

Eccentric Parameters refer to the matrix which transforms coordinates of point P from the world frame to the camera frame. The following equations show the equation involved in the transformation.

$$\begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_w \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_\omega \\ 1 \end{bmatrix} \qquad (2)$$

$$X_c = M_{ext} X_w \qquad (3)$$

Here X_c is the coordinates of point P with respect to the camera frame. The rotation matrix involved in the process is called R, which is the set of r_{ij} (three rows and three columns). This rotation matrix is orthonormal $R^T R = I$; this property is useful in getting back the Eccentric Parameters Matrix (M_{ext}) from the projection matrix (P_m).

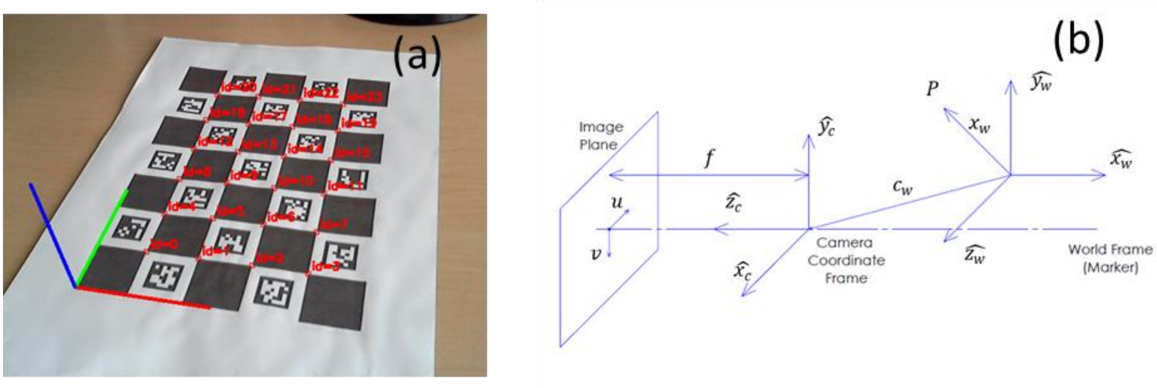

Fig. 4 A typical (a) Marker with world coordinate system (b) Calibration process

Intrinsic Parameters

Intrinsic Parameters refer to the matrix that transforms point *P* coordinates from the camera frame to the coordinates on the image plane (Fig. 5); the following equations describe the transformation.

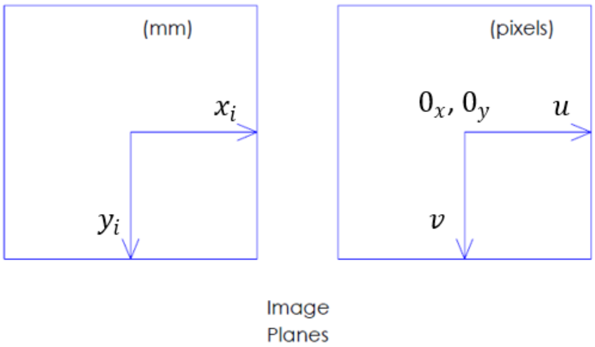

Fig. 5 Transformation of co-ordinates from camera plane to image plane

$$X_c = M_{ext}X_w \tag{4}$$

$$x_i = f\frac{x_c}{z_c}; \qquad y_i = f\frac{y_c}{z_c} \tag{5}$$

$$u' = m_x x_i = m_x f\frac{x_c}{z_c}; \qquad v' = m_y y_i = m_y + \frac{y_c}{z_c} \tag{6}$$

$$u = m_x + \frac{x_c}{z_c} + o_x; \qquad v = m_y f\frac{y_c}{z_c} + a_y \tag{7}$$

$$u = f_x\frac{x_c}{z_c} + O_x; \qquad v = f_y\frac{y_c}{z_c} + O_y \tag{8}$$

In Eqn. 5, *f* is the camera's focal length, and (x_i, y_i) are the coordinates of the point *p* on the image plane in millimeters. Eqn 5 is obtained by using the theory similar triangle ratio. In the

Eq. 6 m_x and m_y are pixel per millimeter constants along the *x* and *y*-axis, respectively. In the images (0, 0) point is considered at the top left corner, but in reality, it is near the center, so an offset of (o_x, o_y) is added along the *x*-axis and *y*-axis. This (o_x, o_y) might not lie at the center due to the lens and sensor misalignment. In the 6th equation, m_x*f is considered as a single variable as f_x for *y*-axis it is f_y, these terms are called effective focal length along the respective axis. These equations can be used to obtain the camera's intrinsic or calibration matrix *(Mint or K)* as shown below.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \equiv \begin{bmatrix} uz_c \\ vz_c \\ z_c \end{bmatrix} = \begin{bmatrix} f_x x_c + z_c o_x \\ f_y y_c + z_c O_y \\ z_c \end{bmatrix} = \begin{bmatrix} f_x & 0 & o_x & 0 \\ 0 & f_y & 0_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix} \qquad (9)$$

$$\begin{bmatrix} uz_c \\ vz_c \\ z_c \end{bmatrix} = \begin{bmatrix} \tilde{u} \\ \tilde{u} \\ z_c \end{bmatrix} = [\mathrm{K}|0]x_c \qquad K = \begin{bmatrix} f_x & 0 & o_x \\ 0 & f_y & o_y \\ 0 & 0 & 1 \end{bmatrix} \qquad (10)$$

K is the calibration matrix, and *[K|0]* is the intrinsic matrix *(Mint)*. *K* is also referred to as camera matrix. As in the projection matrix equation, $w^{\sim}$ is the same as *zc.*

Projection matrix *(Pm)* is found using the least square method by using the known points on the chessboard (Marker). Projection matrix *(Pm)* is given in terms of *Mint* and *Mext* as

$$Pm = Mint*Mext \qquad (11)$$

Therefore

$$u^{\sim} = Pm*Xw \qquad (12)$$

Once the calibration is done, we get the *Mext* and *Mint*, which in our case are the required calibration parameters.

Procedure to be performed for estimating 3D Strain

1. Image Acquisition

Images taken from the normal cameras are prone to distortions, for visualization purposes, these distortions are insignificant, but in the case of computer vision applications, these images should be distortion-free. The most commonly used camera model is the pinhole camera model; it contains radial distortions up to some level. In order correct it we use the following equations

$$\left.\begin{aligned} x_{\text{corrected}} &= x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \\ y_{\text{corrected}} &= y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \end{aligned}\right\} \qquad (13)$$

One more possible distortion is tangential distortion which happens due to misalignment of lens this can be corrected by using the following equations.

$$\begin{aligned} x_{\text{corrected}} &= x + [2p_1xy + p_2(r^2 + 2x^2)] \\ y_{\text{corrected}} &= y + [p_1(r^2 + 2y^2) + 2p_2xy] \end{aligned} \tag{14}$$

$$\text{Distortion coefficients} = (k_1 \quad k_2 \quad p_1 \quad p_2 \quad k_3)$$

2. Gray Scale Conversion:

For the purpose of the strain estimation, only one channel of intensities is enough; using only one channel reduces computational requirements. The following equation is used to convert color images to grayscale.

$$\text{Grayscale}=0.2989*R+0.5870*G+0.1140*B \tag{15}$$

3. Adaptive Thresholding

In simple thresholding, the threshold value is global, i.e., it is the same for all the pixels in the image. Adaptive thresholding is the method where the threshold value is calculated for smaller regions, and therefore, there will be different threshold values for different regions. As the Adaptive thresholding uses local value, it helps to separate edges easily even when some parts of the image have shadows. Gaussian adaptive thresholding algorithm will be implemented for edge segmentation.

4. Morphological Transformation

Morphological transformations such as image opening and closing are used to fill the edges perfectly; this helps in detecting edges with ease.

Once the morphological operations are done with the basic contour detection using the appropriate algorithm, we get the edges of the ellipse or square. The edge points of the square and major and minor axes endpoints of the ellipse are used in determining the real-world dimensions (mm) of the square and ellipse, respectively.

5. Stereo Matching

Stereo matching is the process of using two images from a different view and getting the depth image by knowing the intrinsic parameters of both cameras.

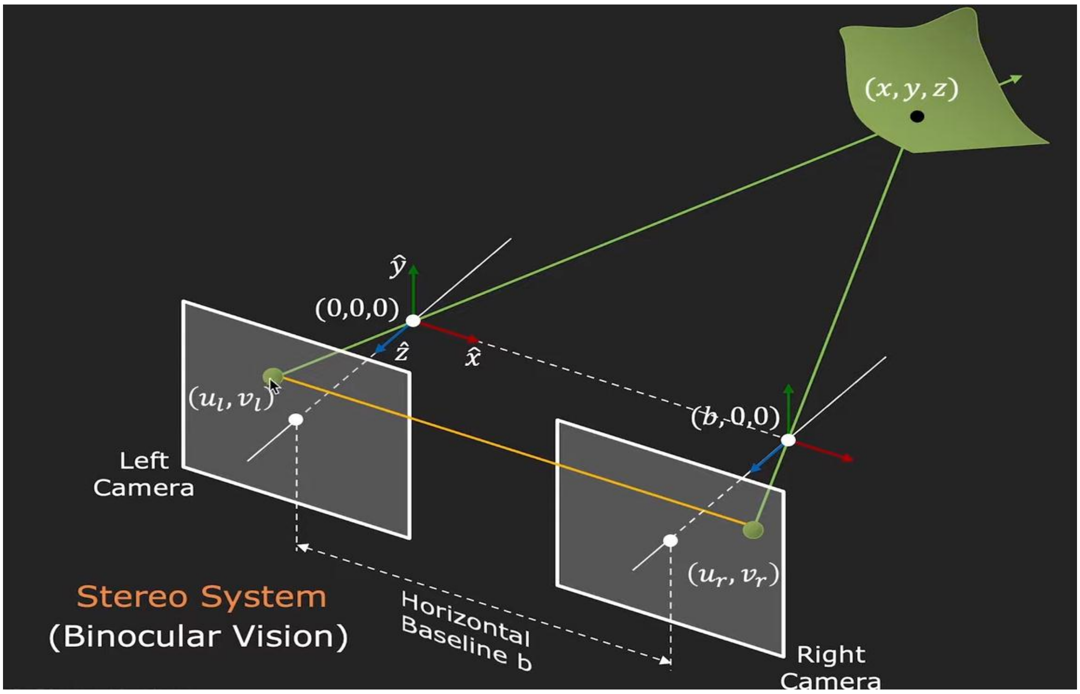

Fig.6 Principle of the stereo vision system

The above Fig. 6 shows the two image planes of the camera; here *b* is the baseline separation between the two cameras. For simple explanation purpose, both images are separated only along *x*-axis but for the 3D strain estimation purpose, the separation along *z*-axis is also needed along with the rotation about the *y*-axis; for that, we use the transformation matrix between two camera frames to obtain the depth information.

The following equation shows the depth estimated at the edge points which we got in the morphological operation section.

$$(u_l, v_l) = \left[f_x \frac{x}{z} + O_x, f_y \frac{y}{z} + O_y\right] \tag{16}$$

$$(u_r, v_r) = \left[f_x \frac{x-b}{z} + O_x, f_y \frac{y}{z} + O_y\right] \tag{17}$$

On solving

$$x = \frac{b(u_i - O_x)}{u_l - u_r} \tag{18}$$

$$y = \frac{bf_x(u_l - O_x)}{f_y(u_l - u_r)} \tag{19}$$

$$z = \frac{bf_x}{u_l - u_r} \tag{20}$$

For the Stereo imaging purpose, both the cameras should be identical. So the effective focal length along the *y* and *x*-axis for both cameras is the same. In the above equations, the (u_l, v_l)

are the image coordinates in the left image, and (u_r,v_r) are the image coordinates in the right image. Parameters fx, fy, Ox, Oy are obtained in the calibration section. Note that here we considered that we know the corresponding point of the same edge in both the left and right image, But in realty, we follow the procedure called window matching to find the corresponding point. To perform the window matching accurately, we need to ensure no pattern repetition in the images. That's why we need to go for random shapes, which enriches the features and reduces pattern repetition.

Once we get the real coordinates of the ellipse or square, strain estimation is a simple logarithmic ratio. The overall methodology of the proposed project is shown in the following flow chart Fig. 7.

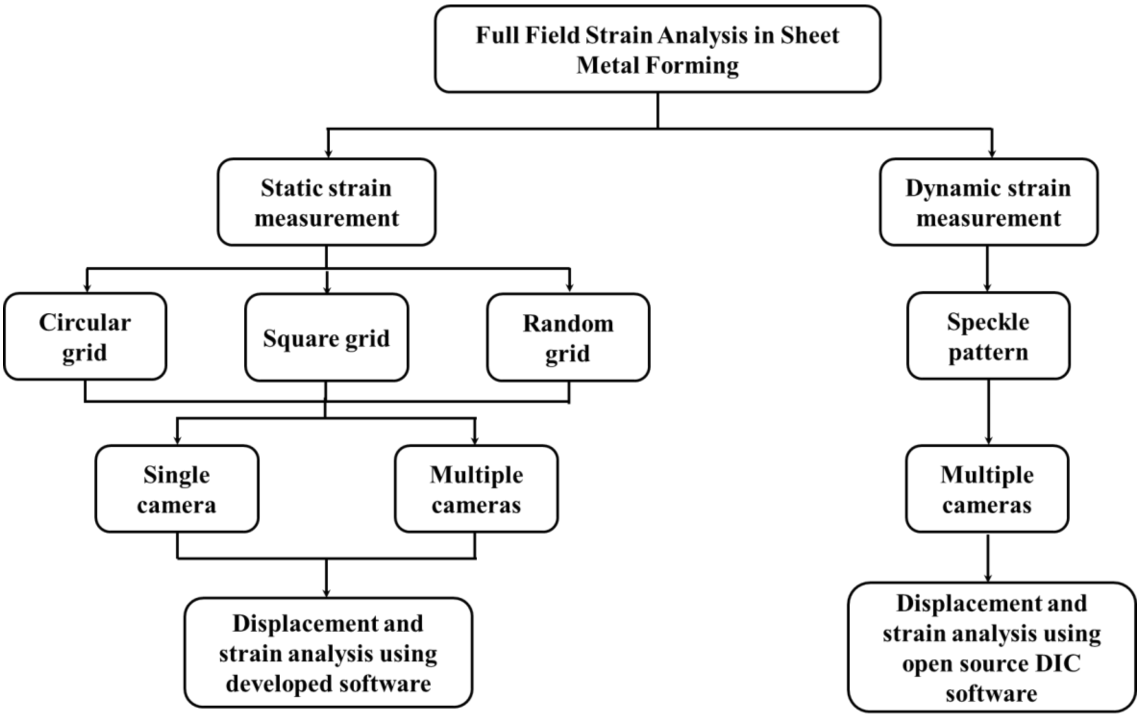

Fig. 7 Overall methodology of the proposed project

3.2 Time schedule of activities

Please give bar chart indicating important activities and time duration from start to end:

Duration (in months) → / Activity ↓	0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
Literature review												
3D static strain measurement – Hardware development												
3D static strain measurement - Software development												
3D dynamic strain measurement – Hardware development												
Integration of dynamic strain measurement system with Multi-DIC												
Testing and validation of developed strain measurement system with commercial system												
Project Report preparation												

3.3 Suggested plan of action for utilizing of research outcome expected from the project

The project is expected to result in the development of hardware and software for 3D static and dynamic strain measurement in sheet metal forming operations. This kind of systems will be very useful in automotive, aerospace, and material testing organizations. We demonstrate the developed system in different industries and research organizations. We also collaborate with industries developing vision-based measuring systems to make it available commercially.

3.4. Environmental impact assessment and risk analysis

There is no environmental risk with the current project.

4. Expertise

4.1 Expertise available with the investigators in executing the project

The PI has recently completed a project on "*Development of image processing based portable device for single point strain analysis for sheet metal forming applications*" sponsored by the

DST-Device development programme. The work done in this project was published in reputed journals, and we are in the process of filing a patent for the developed strain measurement system. The current project is an extension of the earlier DST-DDP project, and the previous project knowledge is immensely helpful in successfully executing the current project.

The Co-PI has recently completed a project on “*Development of the customized below-knee prosthesis using 3D printing technology*" sponsored by DBT. As a part of this project, the Co-PI has used image processing based techniques to reconstruct the 3D model of below-knee from the multiple images. This expertise is very useful in the current project to reconstruct the formed geometry from the multiple images for automatic strain measurement.

4.2 Summary of roles/responsibilities for all investigators

S.No	Name of the investigator	Roles and responsibilities
1.	Kurra Suresh	Development of hardware and integration with software. Sheet metal forming experiments.
2.	Srinivasa Prakash Regalla	Developing the methodology for reconstruction of 3D shape from multiple images

4.3 Key publications published by the Investigators pertaining to the theme of the proposal during the last 5 years

1. Wankhede, P., Kodey, S., Kurra, S., & Radhika, S. (2022). A low cost surface strain measurement system using image processing for sheet metal forming applications. *Measurement*, *187*, 110273.

2. Pankaj W, Radhakrishnan T, Suresh K, Radhika S. (2021). CGA: An image processing based software for surface strain analysis in sheet metal forming. *The Journal of Strain Analysis for Engineering Design*, 56(8), 519-530.

3. Gandla, P. K., Inturi, V., Kurra, S., & Radhika, S. (2020). Evaluation of surface roughness in incremental forming using image processing based methods. *Measurement*, *164*, 108055.

4. Wankhede, P., Kurra, S., & Singh, S. K. (2021). Heat treatment and temperature effects on formability of AA2014-T6 in incremental forming. *Materials and Manufacturing Processes*, 1-9.

5. Gandla, P. K., Kurra, S., Prasad, K. S., Panda, S. K., & Singh, S. K. (2021). Effect of pre-cut hole diameter on deformation mechanics in multi-stage incremental hole flanging of deep drawing quality steel. *Archives of Civil and Mechanical Engineering*, *21*(1), 1-23.

6. Praveen, K. G., & Kurra, S. (2021). Analysis of deformation behavior in various incremental tube forming processes. *Materials and Manufacturing Processes*, *36*(14), 1631-1641.

7. Wankhede, P., Radhakrishnan, T., Radhika, S., & Kurra, S. (2021). Corner detection of a quadrilateral for strain analysis in sheet metal forming by image processing. *Advances in Materials and Processing Technologies*, 1-11.

8. Mohanty, S., Regalla, S. P., & Daseswara Rao, Y. V. (2019). Robot-assisted incremental sheet metal forming under the different forming condition. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *41*(2), 1-12.

9. Mohanty, S., Regalla, S. P., & YV, D. R. (2018). Investigation of influence of part inclination and rotation on surface quality in robot assisted incremental sheet metal forming (RAISF). *CIRP Journal of Manufacturing Science and Technology*, *22*, 37-48.

10. Srinivasa Prakash Regalla and Prakash Narayan Shrivastava, “Method and System to Generate Personalized Data for Prosthetic Manufacturing”, (Final patent application filed), Application No. 4219/CHE/2015.

11. Srinivasa Prakash Regalla and Prakash Narayan Shrivastava, "A process for manufacturing a prosthetic limb socket and the socket thereof", Indian Final Patent Application No. 201841035329, Date of Filing: September 19, 2018.

4.4 Bibliography

1. Bagheriasl, R., & Worswick, M. J. (2015). Formability of AA3003 brazing sheet at elevated temperatures: limiting dome height experiments and determination of forming limit diagrams. *International Journal of Material Forming*, *8*(2), 229-244.
2. Bandyopadhyay, K., Basak, S., Panda, S. K., & Saha, P. (2015). Use of stress based forming limit diagram to predict formability in two-stage forming of tailor welded blanks. *Materials & Design*, *67*, 558-570.
3. Barnwal, V. K., Tewari, A., Narasimhan, K., & Mishra, S. K. (2016). Effect of plastic anisotropy on forming behavior of AA-6061 aluminum alloy sheet. *The Journal of Strain Analysis for Engineering Design*, *51*(7), 507-517.
4. Bhargava, M., Tewari, A., & Mishra, S. K. (2015). Forming limit diagram of Advanced High Strength Steels (AHSS) based on strain-path diagram. *Materials & Design*, *85*, 149-155.

5. Chaimongkon, T., Panich, S., & Uthaisangsuk, V. (2021). Anisotropic fracture forming limit curve and its applications for sheet metal forming with complex strain paths of aluminum sheet. *The International Journal of Advanced Manufacturing Technology*, *115*(11), 3553-3577.
6. Cui, Z., Xia, Z. C., Ren, F., Kiridena, V., & Gao, L. (2013). Modeling and validation of deformation process for incremental sheet forming. *Journal of Manufacturing Processes*, *15*(2), 236-241.
7. Ghosal, P., & Paul, S. K. (2020). Effect of specimen orientation to the rolling direction on uniaxial tensile forming and failure limits. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *234*(13), 1598-1603.
8. Huang, G., Yan, B., & Xia, Z. (2011). Measurement of r-values of high strength steels using digital image correlation. *SAE International Journal of Materials and Manufacturing*, *4*(1), 385-395.
9. Kotkunde, N., Krishna, G., Shenoy, S. K., Gupta, A. K., & Singh, S. K. (2017). Experimental and theoretical investigation of forming limit diagram for Ti-6Al-4 V alloy at warm condition. *International Journal of Material Forming*, *10*(2), 255-266.
10. Kumar, P., & Tandon, P. (2022). Investigating the capability of the Lemaitre damage model to establish the incremental sheet forming process. *Archives of Civil and Mechanical Engineering*, *22*(2), 1-18.
11. Merklein, M., Kuppert, A., & Affronti, E. (2014). An improvement of the time dependent method based on the coefficient of correlation for the determination of the forming limit curve. In *Advanced Materials Research* (Vol. 1018, pp. 215-222). Trans Tech Publications Ltd.
12. Min, J., Stoughton, T. B., Carsley, J. E., & Lin, J. (2017). Comparison of DIC methods of determining forming limit strains. *Procedia Manufacturing*, *7*, 668-674.
13. Panich, S., Liewald, M., & Uthaisangsuk, V. (2018). Stress and strain based fracture forming limit curves for advanced high strength steel sheet. *International Journal of Material Forming*, *11*(5), 643-661.
14. Paul, S. K., Roy, S., Sivaprasad, S., & Tarafder, S. (2019). Forming limit diagram generation from in-plane uniaxial and notch tensile test with local strain measurement through digital image correlation. *Physical Mesomechanics*, *22*(4), 340-344.
15. Pérez Caro, L., Schill, M., Haller, K., Odenberger, E. L., & Oldenburg, M. (2020). Damage and fracture during sheet-metal forming of alloy 718. *International Journal of Material Forming*, *13*(1), 15-28.
16. Peterkova, E., & Srefl, M. A. R. T. I. N. (2016). Use of 3D measuring system aramis for analysis of tube flaring process. *MM Science Journal*, (2016), 1392-1397.
17. Quach, H., & Kim, Y. S. (2021). Effect of non-associated flow rule on fracture prediction of metal sheets using a novel anisotropic ductile fracture criterion. *International Journal of Mechanical Sciences*, *195*, 106224.
18. Rencheck, M., Zelenak, P., Shang, J., & Kim, H. (2017). *Evaluation of DIC based forming limit curve methods at various temperatures of aluminum alloys for automotive applications* (No. 2017-01-0309). SAE Technical Paper.
19. Rosa-Sainz, A., Centeno, G., Silva, M. B., López-Fernández, J. A., Martínez-Donaire, A. J., & Vallellano, C. (2021). On the Determination of the Forming Limits by Necking

and Fracture of Polycarbonate Sheet. In *Forming the Future* (pp. 2597-2608). Springer, Cham.
20. Sajun Prasad, K., Panda, S. K., Kar, S. K., Sen, M., Murty, S. V. S., & Sharma, S. C. (2017). Microstructures, forming limit and failure analyses of inconel 718 sheets for fabrication of aerospace components. *Journal of Materials Engineering and Performance*, *26*(4), 1513-1530.
21. Satheeshkumar, V., & Narayanan, R. G. (2016). Experimental evaluation and prediction of formability of adhesive bonded steel sheets at different adhesive properties. *Journal of Testing and Evaluation*, *44*(3), 1294-1306.
22. Sekhar, K. C., Narayanasamy, R., & Venkateswarlu, K. (2014). Formability, fracture and void coalescence analysis of a cryorolled Al–Mg–Si alloy. *Materials & Design*, *57*, 351-359.
23. Song, Y., Green, D. E., & Rose, A. (2020). Investigation of various necking criteria for sheet metal formability analysis using digital image strain data. *International Journal of Material Forming*, *13*(6), 1015-1024.
24. Vadavadagi, B. H., Bhujle, H. V., & Khatirkar, R. K. (2020). Forming Limit Diagrams of Low-Carbon Steels Obtained Using Digital Image Correlation Technique and Enhanced Formability Predictions Incorporating Microstructural Developments. *Journal of Materials Engineering and Performance*, *29*(9), 6066-6077.
25. Velmanirajan, K., Anuradha, K., Syed Abu Thaheer, A., Narayanasamy, R., Madhavan, R., & Suwas, S. (2014). Experimental investigation of forming limit, void coalescence and crystallographic textures of aluminum alloy 8011 sheet annealed at various temperatures. *Archives of Civil and Mechanical Engineering*, *14*(3), 398-416.
26. Vitu, L., Laforge, N., Malécot, P., Boudeau, N., Manov, S., & Milesi, M. (2018, May). Characterization of zinc alloy by sheet bulging test with analytical models and digital image correlation. In *AIP Conference Proceedings* (Vol. 1960, No. 1, p. 150015). AIP Publishing LLC.
27. Zheng, Q., Mashiwa, N., & Furushima, T. (2020). Evaluation of large plastic deformation for metals by a non-contacting technique using digital image correlation with laser speckles. *Materials & Design*, *191*, 108626.

5. List of Projects submitted/implemented by the Investigators

5.1 Details of the projects submitted to various funding agencies

S.No	Title	Cost in Lakhs	Month of submission	Role as PI/Co-PI	Agency	Status
-	-	-	-	-	-	-

5.2 Details of the projects under implementation

Dr. Kurra Suresh (PI)

S.No	Title	Cost in Lakhs	Start Date	End Date	Role as PI/Co-PI	Agency
1.	Theoretical and Simulation Based Approach to Determine the Forming Limit Diagrams of beta-Ti alloys at Elevated Temperatures	26.506 (BITS Share: 15.506)	June 2020	June 2023	PI	DRDO-ARDB
2.	Enhanced strength to weight ratio of Inconel 718 alloy structures made by additive manufacturing for aerospace applications	25.33	March 2021	Feb 2024	Co-PI	DST-SERB

Prof. Srinivasa Prakash Regalla (Co-PI)

S.No	Title	Cost in Lakhs	Start Date	End Date	Role as PI/Co-PI	Agency
1	Enhanced strength to weight ratio of Inconel 718 alloy structures made by additive manufacturing for aerospace applications	25.33	March 2021	Feb 2024	PI	DST-SERB

5.3 Details of the projects completed in the last 5 years

<u>Dr. Kurra Suresh (PI)</u>

S.No	Title	Cost in Lakhs	Start Date	End Date	Role as PI/Co-PI	Agency
1.	Development of Image Processing Based Portable Device to Measure Surface Strains in Sheet Metal Forming	18.137	Feb 2018	Feb 2022	PI	DST-DDP

<u>Prof. Srinivasa Prakash Regalla (Co-PI)</u>

S.No	Title	Cost in Lakhs	Start Date	End Date	Role as PI/Co-PI	Agency
1.	Develop and Test Certain 3D Printing Technologies To Produce Innovative Limbs At Affordable Costs for the Disabled in India	47.65	Feb 2015	Dec 2016	PI	BIRAC/DBT
2	Study of lubricant and application method for enhanced surface finish and reduced draw load on cold drawn steel tubes	26.62	Aug 2017	July 2020	Co-PI	Tube Investments India Limited, Chennai

6. List of facilities being extended by parent institution(s) for the project Implementation.

6.1 Infrastructural Facilities

Sr.No.	Infrastructural Facility	Yes/No/ Not required Full or sharing basis
1.	Workshop Facility	Yes
2.	Water & Electricity	Yes
3.	Laboratory Space/ Furniture	Yes
4.	Power Generator	Yes
5.	AC Room or AC	Yes
6.	Telecommunication including e-mail & fax	Yes
7.	Transportation	No

8.	Administrative/ Secretarial support	Not required
9.	Information facilities like Internet/Library	Yes
10.	Computational facilities	Yes
11.	Animal/Glass House	Not required
12.	Any other special facility being provided	No

6.2 Equipment available with the Institute/ Group/ Department/Other Institutes for the project:

Equipment available with	Generic Name	Model, Make & Year	Remarks including accessories available and current usage of equipment
PI's Department	3-axis CNC milling machine	Hardinge Bridgeport, Germany, 2010 BFW, India, 2020.	Used for machining
	100 kN Universal Testing Machine	Z100, Zwick, Germany 2018	Used for material testing at room temperature, elevated temperatures and cryogenic conditions.
	CNC Wire Electric Discharge Machining (WEDM)	Electronica-Sprint cut, Pune, Year of purchase:2013	Used for specimen preparation for material testing and forming
	40 Ton Hydraulic Press	J. Ragrau Instruments, New Delhi, 2015	Used for performing sheet metal forming
	Grid marking equipment	Etch-On Marks Control, India Year of purchase:2013	Used for grid marking in formability analysis
	Stereo Microscope	Olympus, 2018	
PI's			
Other Institute(s)			

7. Name and address of experts/institution interested in the subject/outcome of the project

Name and address of experts:

1. **Prof. D. Ravi Kumar**, Department of Mechanical Engineering, Indian Institute of Technology, Delhi. Email: dravi@mech.iitd.ac.in; Phone: (91)-11-26591144.

2. **Prof. Sushanta Kumar Panda**, Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur. Email: sushanta.panda@mech.iitkgp.ernet.in; Phone: +91-3222-282910

3. **Prof. Ganesh Narayanan**, Department of Mechanical Engineering, Indian Institute of Technology, Guwahati. Email: ganu@iitg.ernet.in; Phone:+91-361-258 2669.

4. **Mr. Gopi G**, Scientist 'F', Defence Research and Development Laboratory (DRDL), Hyderabad. Email: gopi_593@yahoo.com; Phone: +91 9948661980.

5. **Dr. G. Manikandan**, Principal Researcher, TATA steel,

Email: manikandan.g@tatasteel.com, Phone: 07639071614.

Institutions interested in the subject/outcome of the project:

1. Ashok Leyland, Chennai.
2. Maruti Suzuki India Limited, Noida
3. Mahindra and Mahindra Limited, Chennai.
4. Tube Investments of India, Chennai.
5. Tata Steel Limited – Tatanagar.
6. Development Laboratory (DRDL), Hyderabad.
7. Defence Metallurgical Research Laboratory (DMRL), Hyderabad
8. National Aerospace Laboratories – Bengaluru.
9. Indira Gandhi Centre For Atomic Research – Kalpakkam.
10. Vikram Sarabhai Space Centre – Thiruvananthapuram

Budget Details

Institution wise Budget Breakup :

Budget Head	Birla Institute of Technology & Science Pilani, Hyderabad Campus	Total
Research Personnel	11,64,000	**11,64,000**
Consumables	2,50,000	**2,50,000**
Travel	1,50,000	**1,50,000**
Equipment	6,00,000	**6,00,000**
Contingencies	90,000	**90,000**
Overhead	2,25,400	**2,25,400**
Total	**24,79,400**	**24,79,400**

Institute Name : *Birla Institute of Technology & Science Pilani, Hyderabad Campus*

Year Wise Budget Summary (Amount in INR) :

Budget Head	Year-1	Year-2	Year-3	Total
Research Personnel	3,72,000	3,72,000	4,20,000	**11,64,000**
Consumables	1,00,000	1,00,000	50,000	**2,50,000**
Travel	50,000	50,000	50,000	**1,50,000**
Equipments	6,00,000	0	0	**6,00,000**
Contingencies	30,000	30,000	30,000	**90,000**
Overhead	90,200	80,200	55,000	**2,25,400**
Grand Total	**12,42,200**	**6,32,200**	**6,05,000**	**24,79,400**

Research Personnel Budget Detail (Amount in INR) :

Designation	Year-1	Year-2	Year-3	Total
Junior Research Fellow *The project work involves extensive experimental work such as developing the required hardware for strain measurement and performing sheet metal forming experiments. Moreover the project also demands in dept knowledge in image processing and Python language to develop the software for full field strain analysis. Hence, it is essential to have one M. Tech candidate as JRF for successful completion of project.*	3,72,000	3,72,000	4,20,000	**11,64,000**

Consumable Budget Detail (Amount in INR) :

Justification	Year-1	Year-2	Year-3	Total
The consumables amount will be used to fabricate the test rig to hold the cameras for 3D static and dynamic strain measurement. To procure the metal sheets for forming. To procure the electrolytes for grid printing. Other chemicals and tool kits required for fabrication work.	1,00,000	1,00,000	50,000	**2,50,000**

Travel Budget Detail (Amount in INR) :

Justification (Inland Travel)	Year-1	Year-2	Year-3	Total
This amount will be used attending review meetings, conferences and to visit other research labs for discussions. This amount will also used for traveling to other labs for testing and validating developed strain measurement system with commercial system. The cost includes travel of PI, Co-PI and JRF.	50,000	50,000	50,000	**1,50,000**

Equipment Budget Detail (Amount in INR) :

Generic Name ,Model No. , (Make)/ Justification	Quantity	Spare time	Estimated Cost
Cameras and Rotary table (Raspberry Pi) *The equipment budget will be used to procure the required cameras and rotary table to build the full-field strain measurement system.*	1	25 %	**6,00,000**

Contingency Budget Detail (Amount in INR) :

Justification	Year-1	Year-2	Year-3	Total
Contingency amount is used to procure necessary books, stationary items, research publications, typing, printing and some spare parts required for research work	30,000	30,000	30,000	**90,000**

Overhead Budget Detail (Amount in INR) :

Justification	Year-1	Year-2	Year-3	Total
The institute overhead may be utilized for providing infrastructural facilities such as office support, administrative and accounts service, any repair works of the equipment during project tenure.	90,200	80,200	55,000	**2,25,400**

BIO-DATA (PI)

1. Name and full correspondence address

Kurra Suresh
Mechanical Engineering Department,
BITS-Pilani Hyderabad Campus,
Jawaher Nagar, Shameerpet Mandal,
R.R. District, Hyderabad-500078,
Telangana, India.

2. Email(s) and contact number(s)

Email(s) ksuresh.iitd@gmail.com,
ksuresh@hyderabad.bits-pilani.ac.in
Contact +91-40 66303570
+91-9701189052

3. Institution: Birla Institute of Technology and Science (BITS) Pilani Hyderabad Campus

4. Date of Birth: 01 July 1980

5. Gender (M/F/T): M

6. Category Gen/SC/ST/OBC: Gen

7. Whether differently abled (Yes/No): No

8. Academic Qualification (Undergraduate Onwards)

S.No	Degree	Year	Subject	Institution/University	% Marks
1.	B.E	2002	Mechanical Engineering	Andhra University	74.62%
2.	M.Tech	2005	Production Engineering	IIT Delhi	8.609
3.	Ph.D	2015	Sheet Metal Forming	BITS Pilani	---

9. Ph.D thesis title, Guide Name, Institute/Organization/University, Year of Award.

PhD thesis title: ‘Finite Element Studies and Experimental Validation of Asymmetric Incremental Sheet Forming of Extra Deep drawing Steel’

Guide name: Prof. Srinivasa Prakash Regalla, Professor, Mechanical Engineering Department.

Institute: BITS- Pilani University

Year of Award: 2015

10. Work experience (in chronological order):

S.No	Position held	Name of the Institute	From	To	Pay scale
1.	Assistant Professor	BITS-Pilani, Hyderabad Campus	30 Dec 2015	Till date	1,35,300 (Basic)
2.	Lecturer	BITS-Pilani, Hyderabad Campus	17 Aug. 2009	29 Dec 2015	15000-39100 (7000)
3.	Assistant Professor	SNIST-Hyderabad	29 March 2009	25 July 2009	15000-39100 (7000)
4.	Assistant Professor	GRIET - Hyderabad	28 May 2007	25 Feb 2009	8000-275-13500
5.	Assistant Professor	DRKIST - Hyderabad	12 July 2006	08 May 2007	8000-275-13500
6.	Assistant Professor	SNIST-Hyderabad	18 July 2005	07 July 2006	8000-275-13500

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant.

S.No	Name of the Award	Awarding Agency	Year
1.	GATE scholarship	MHRD, Govt. of India	2003-2005
2.	Merit Scolarship	Jindal Educational Trust	2000-2002

12. Publications *(List of papers published in SCI Journals, in year wise descending order*

S.No	Author(s)	Title	Name of Journal	Volume	Page	Year
1.	Wankhede, P., Kodey, S., Kurra, S., & Radhika, S.	A low cost surface strain measurement system using image processing for sheet metal forming applications	*Measurement (IF:3.927)*	187	110273	2021
2.	Wankhede, P., Kurra, S., & Singh, S. K.	Heat treatment and temperature effects on formability of	*Materials and Manufacturing Processes (IF:4.616)*	Online	1-9	2021

		AA2014-T6 in incremental forming				
3.	Pankaj, W., Radhakrishnan, T., Suresh, K., & Radhika, S.	CGA: An image processing based software for surface strain analysis in sheet metal forming	*The Journal of Strain Analysis for Engineering Design (IF:1.541)*	56(8)	519-530	2021
4.	Pandre, S., Morchhale, A., Kotkunde, N., & Kurra, S.	Processing of DP590 steel using single point incremental forming for automotive applications	*Materials and Manufacturing Processes (IF:4.616)*	*36*(14)	1658-1666	2021
5.	Pandre, S., Morchhale, A., Mahalle, G., Kotkunde, N., Suresh, K., & Singh, S. K.	Fracture limit analysis of DP590 steel using single point incremental forming: experimental approach, theoretical modeling and microstructural evolution	*Archives of Civil and Mechanical Engineering (IF:4.369)*	21(3)	1-20	2021
6.	Praveen, K. G., & Kurra, S	Analysis of deformation behavior in various incremental tube forming processes	*Materials and Manufacturing Processes (IF:4.616)*	36(14)	1631-1641	2021

7.	Gandla, P. K., Kurra, S., Prasad, K. S., Panda, S. K., & Singh, S. K.	Effect of pre-cut hole diameter on deformation mechanics in multi-stage incremental hole flanging of deep drawing quality steel	*Archives of Civil and Mechanical Engineering (IF:4.369)*	*21*(1)	1-23	2021
8.	Gandla, P. K., Inturi, V., Kurra, S., & Radhika, S.	Evaluation of surface roughness in incremental forming using image processing based methods	*Measurement (IF:3.927)*	164	108055	2020
9.	Saxena, A., Kumaraswamy, A., Kotkunde, N., & Suresh, K.	Constitutive modeling of high-temperature flow stress of armor steel in ballistic applications: a comparative study	*Journal of Materials Engineering and Performance (IF:1.819)*	*28*(10)	6505-6513	2019
10.	Singh, S. K., Limbadri, K., Singh, A. K., Ram, A. M., Ravindran, M., Krishna, M., ., Kurra, S., & Panda, S. K.	Studies on texture and formability of Zircaloy-4 produced by pilgering route.	*Journal of Materials Research and Technology (IF:5.039)*	*8*(2)	2120-2129	2019
11.	Suresh Kurra, Nasih HR, Regalla SP, Gupta AK	Parametric study and multi-objective optimization in single-point	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of*	230(5)	825-837	2016

		incremental forming of extra deep drawing steel sheets	*Engineering Manufacture (IF:2.610)*			
12.	Suresh Kurra, Bagade SD, Regalla SP	Deformation Behavior of Extra Deep Drawing Steel in Single-Point Incremental Forming	*Materials and Manufacturing Processes (IF:4.616)*	30(10)	1202-1209	2015
13.	Kurra, S., Rahman, N. H., Regalla, S. P., & Gupta, A. K.	Modeling and optimization of surface roughness in single point incremental forming process	*Journal of Materials Research and Technology (IF:5.039)*	*4*(3)	304-313	2015
14.	Kurra, S., & Regalla, S. P.	Experimental and numerical studies on formability of extra-deep drawing steel in incremental sheet metal forming	*Journal of Materials Research and Technology (IF:5.039)*	*3*(2)	158-171	2014

13. Detail of patents.

S.No	Patent Title	Name of Applicant(s)	Patent No	Award Date	Agency/Country	Status
1.	-	-	-	-	-	-

14. Books/Reports/Chapters/General articles etc.

S.No	Title	Author's Name	Publisher	Year of Publication
1.	-	-	-	-

15. Any other Information (maximum 500 words):

--Nil--

PROFORMA FOR BIO-DATA (to be uploaded)

1. Name and full correspondence address:	**Dr. Srinivasa Prakash Regalla, PhD** Professor, Department of Mechanical Engineering Birla Institute of Technology & Science Pilani Hyderabad Campus, Jawahar Nagar, Shamirpet Mandal Hyderabad – 500078, Telangana State.
2. Email(s) and contact number(s)	E-mail: regalla@hyderabad.bits-pilani.ac.in spr.bits@gmail.com Mobile: 9010202879
3. Institution	Birla Institute of Technology & Science Pilani
4. Date of Birth	5th Aug 1968
5. Gender (M/F/T)	Male
6. Category Gen/SC/ST/OBC	General
7. Whether differently abled (Yes/No)	No

8. Academic Qualification (Undergraduate Onwards)

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S. No.	Degree	Year	Subject	University/Institute	% Marks/Grade
1	B. Tech.	1990	Mechanical Engineering	Kakatiya University, Warangal	76.3%, First Class with Distinction, 2nd Rank in the Class
2	M. Tech.	1992	Mechanical Engineering with specialization in Manufacturing Science	IIT Kanpur	8.32/10; Thesis satisfactory
3	Ph.D.	1998	Mechanical Engineering. Thesis title: "Evaluation of Boundary Friction under Sub-surface Plastic Deformation for Metal Forming Processes"	IIT Delhi	Course work: 10/10 GPA

9. Ph.D thesis title, Guide's Name, Institute/Organization/University, Year of Award.

Title: Evaluation of Boundary Friction under Sub-surface Plastic Deformation for Metal Forming Processes

Guides' Name: Prof. U. R. K. Rao (Main Guide), Prof. A. Sethuramaiah (Co-Guide)
Institute: Indian Institute of Technology Delhi (IIT Delhi)
Year of Award: 1998

10. Work experience (in chronological order).

S. No.	Position Held	Name of Institute	From	To	Pay Scale (Rs.)
1	Professor	BITS-Pilani (Hyderabad Campus)	July 2010	Till date	53000-no cap. AGP=10500
2	Associate Professor	BITS-Pilani (Hyderabad Campus)	Dec 2008	June 2010	37,400-67,000 (Min.45,500), AGP=9500
3	Associate Professor	BITS-Pilani, Pilani Campus, Vidya Vihar, Pilani, Rajasthan	Jan 2005	Dec 2008	37,400-67,000 (Min.45,500), AGP=9500
4	Assistant Professor	BITS-Pilani, Pilani Campus, Vidya Vihar, Pilani, Rajasthan	Oct 1998	Dec 2004	37,400-67,000 (Min.37,400), AGP=9500
5	Guest Researcher	NIST, Gaithersburg, Maryland, USA	Jan 1998	Oct 1998	USD 1800 pm.
6	Research Associate during	IIT Delhi	Sept 1997	Dec 1997	5000 pm
7	Senior Research Associate	IIT Kanpur	April 1992	Dec 1992	3500 pm.

Also worked as:

- Assistant Dean, Research and Consultancy, Jan 2006 to Nov 2008, BITS Pilani, Vidya Vihar, Pilani, Rajasthan.
- Head of the Department of Mechanical Engineering at BITS-Pilani (Hyderabad Campus) from Aug 2009 to Dec 2012.
- Professor-in-charge, Faculty Affairs, at BITS-Pilani (Hyderabad Campus) from Aug 2013 to Jan 2014.
- Associate Dean, Work Integrated Learning Programmes Division at BITS-Pilani, Hyderabad Campus, from Feb 2014 till date.

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant.

S. No.	Name of Award	Awarding Agency	Year
1	GATE Scholarship in M.Tech at IIT Kanpur	MHRD, Govt of India	July 1990 to Dec 1991
2	GATE Scholarship in PhD at IIT Delhi	MHRD, Govt of India	Jan 1993 to Sept 1997
3	India-USA Exchange Visitor Scientist	NIST, Gaithersburg, MD, USA	Jan 1998 to Sept 1998
4	Marquis "Who is Who in Engineering" in World,	MarquisWho is Who	2005

5	(jointly with co-author) best paper medal award	ICAT-2014, NIT Calicut, India	2014
6	Invited Speaker, First International Conference on Progress in Additive Manufacturing (Pro-AM-2014)	Nanyang Technological University (NTU), Singapore	2014
7	BIG-5 research grantee	BIRAC (Dept of Biotechnology, Govt of India)	2015
8	Keynote Speaker, Fifth International Conference on Materials Processing and Characterization	GKRIET, Hyderabad	2016
9	Distinguished Alumni award	Kakatiya Institute of Technology and Science Warangal (an Autonomous Engineering Institute)	2015
10	BIG-5 Research Grant	BIRAC (Dept of Biotechnology, Govt of India)	2015

12. Publications *(List of papers published in SCI Journals, in year wise descending order)*

S. No	Author(s)	Title	Name of Journal	Volume	Page	Year
1	Kurra Suresh, Masih M.H., **Srinivasa Prakash Regalla**, Amit Kumar Gupta	Parametric Study and Multi-objective Optimization in Single Point Incremental Forming of EDD Steel Sheets	Proceedings of IMechE, Part B: Journal of Engineering Manufacture	230 (5)	825-837	2016
2	V Vijayaraghavan, A Garg, CH Wong, K Tai, **Srinivasa Prakash Regalla**, MC Tsai	Density characteristics of laser-sintered three-dimensional printing parts investigated by using an integrated finite element analysis–	Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	230	100-110	2016

		based evolutionary algorithm approach				
3	Kurra Suresh, Sree Divya Bagade, **Srinivasa Prakash Regalla**	Deformation Behavior of Extra Deep Drawing Steel in Single Point Incremental Forming	Materials and Manufacturing Processes	30(10)	1202-1209	2015
4	G. Pavan Kumar, **Srinivasa Prakash Regalla**	Part Strength Evolution with Bonding between Filaments in Fused Deposition Modeling	Virtual and Physical Prototyping	9(3)	141-149	2014
5	G. Pavan Kumar and **Srinivasa Prakash Regalla**	Multi-objective optimization of strength and volumetric shrinkage of FDM parts	Virtual and Physical Prototyping	9(2)	127-138	2014
6	Singh A. K. and **Regalla Srinivasa Prakash**	DOE Based Three Dimensional Finite Element Analysis for Predicting Density of a Laser Sintered Part	Rapid Prototyping Journal	16(6)	460-467	2010
7	P. Eswar Verma, **Regalla Srinivasa Prakash**, U. R. K. Rao	Roundness Error In Cylidrical Machined Parts Due To Dynamics Of Spindle Rotation In High Speed Machining	Advances in Vibration Engineering	6 (3)	221-242	2007

8	**Regalla Srinivasa Prakash**, U. R. K. Rao and A. Sethuramaiah	Some Studies on Friction and Scuffing in Boundary Lubricated Sliding Contact with Subsurface Plastic Deformation	Industrial Lubrication and Tribology	59 (1)	29-37	2007
9	**Regalla Srinivasa Prakash** and U. R. K. Rao	A Study on the Boundary Lubricated Sliding Contact with Subsurface Plastic Deformation	STLE Tribology Transactions	48(2)	250-258	2005
10	**Regalla Srinivasa Prakash**, P. M. Dixit, G. K. Lal	Steady State Plane-Strain Cold Rolling of a Strain-Hardening Material	Journal of Materials Processing Technology	52	338-358	1995

13. Detail of patents

S. No.	Patent Title	Name of the applicant(s)	Patent No.	Award Date	Agency/Country	Status
1	Method and System to Generate Personalized Data for Prosthetic Manufacturing	**Srinivasa Prakash Regalla** and Prakash N. Shrivastava	4219/CHE/2015	13/08/2015	India	Provisional patent filed; full patent is to be filed soon
2	A Novel Deep Drawing Tooling with Selective Heating and Cooling for	V.V.N. Satya Suresh and Srinivasa Prakash Regalla	4038/CHE/2015	04/08/2015	India	Provisional patent filed; full patent is to be filed soon

	Tailor Welded Blanks (TWBs)					

14. Books/Reports/Chapters/General articles etc.

S. No.	Title	Author's Name	Publisher	Year of Publication
1	Computer Aided Analysis and Design	Srinivasa Prakash Regalla	IK International Publishers, New Delhi	2010
2	Product Design and Manufacturing: A product lifecycle approach	Srinivasa Prakash Regalla and Kuldip Singh Sangwan	New Age International Publishers, New Delhi	2014

15. Any other Information (maximum 500 words)

Summary of Biodata:
Dr. Srinivasa Prakash Regalla obtained his PhD in 1998 on *Evaluation of Boundary Friction under Sub-surface Plastic Deformation for Metal Forming Processes* from IIT Delhi. He obtained his M.Tech. in 1992 with specialization of Manufacturing science/Mechanical Engineering from IIT Kanpur, where he carried out his thesis work on finite element analysis of steady state cold rolling of strain hardening material. He obtained his B.Tech. in 1990 in Mechanical Engineering from Kakatiya University, Warangal, where he was awarded a silver medal for academic excellence and standing second in the rank position in the class for cumulative four years of academic performance. In 2015, his undergraduate college honored him with the *distinguished alumni award* for overall achievements in the academic career. He has 20 research experience, which includes 17 years of teaching and brief industrial experience. He taught courses both at the undergraduate level and postgraduate level, both to the University students and industrial working professionals, in design and manufacturing engineering and is credited with the development of several new core and elective courses. He worked in the Manufacturing Systems Integration Division (MSID) at the NIST, Gaithersburg, Maryland, USA in 1998 as a Guest Researcher, during which he carried out research in the engineering design technologies related to national advanced manufacturing testbed (NAMT). He authored around 65 research papers in reputed international journals and conference proceedings, around 7 research papers in national conferences, 2 papers in national journals/technical magazines, 2 books on design and manufacturing and filed 2 provisional patents in the area of prosthetics and tailor welded blank forming. He supervised 3 completed PhD students and currently supervising 6 PhD students. He supervised 23 higher degree (M.E.) dissertation works and 35 first degree (B.E.) thesis works. His current research interests are Additive Manufacturing, Sheet Metal Forming, CAD/CAM/CIM/CAE/PLM, Metalworking Tribology, Medical Device Design and Manufacturing. He is a recipient of the prestigious BIG-5 grant of BIRAC, Department of Biotechnology, Government of India for carrying out research in the area of application of CAD/CAM technologies in medical device manufacturing. He delivered around 12 invited and keynote lectures in reputed conferences including one on recent trends in additive manufacturing at the NTU, Singapore in 2014 and another at the fifth international conference on materials

processing and characterization at GKRIET, Hyderabad. He is a member of ASME, TSI, IEI and SAE. Currently he is a Professor of Mechanical Engineering and Associate Dean of WILP at BITS Pilani, Hyderabad Campus.

Birla Institute of Technology & Science, Pilani
Hyderabad Campus

Endorsement from the Head of the Institution of PI

This is to certify that:

1 Institute welcomes participation of Name: **Dr. Kurra Suresh** Designation: **Assistant Professor** as the Principal Investigator and **Prof. Srinivasa Prakash Regalla.** as the Co-Investigator/s for the project titled "***Development of a low cost 3D DIC system for surface strain analysis in sheet metal forming operations***" and that in the unforeseen event of discontinuance by the Principal Investigator, the Co-Investigator will assume the responsibility of the fruitful completion of the project with the approval of SERB.

2 The PI, **Dr. Kurra Suresh** is a permanent or regular employee of this Institute / University / Organization and has **20** years of regular service left before superannuation.

3 The project starts from the date on which the University/Institute/ Organization/College receives the grant from SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi.

4 The investigator will be governed by the rules and regulations of University/ Institute/Organization/College and will be under administrative control of the University/ Institute/Organization/College for the duration of the project.

5 The grant-in-aid by the SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi will be used to meet the expenditure on the project and for the period for which the project has been sanctioned as mentioned in the sanction order.

6 No administrative or other liability will be attached to SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi at the end of the project.

7 The University/Institute/Organization/College will provide basic infrastructure and other required facilities to the investigator for undertaking the research project.

8 The University/ Institute/Organization/College will take into its books all assets created in the above project and its disposal would be at the discretion of SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi.

9 The University/ Institute/Organization/College assumes to undertake the financial and other management responsibilities of the project.

Dated: 29.04.2022

Signature of the Head of Institution
Seal of Institution

Deputy Registrar
BITS Pilani, Hyderabad Campus
Jawaharnagar, Kapra Mandal
Medchal District-500 078
Telangana State, India

Birla Institute of Technology & Science, Pilani
Hyderabad Campus, Jawahar Nagar, Kapra Mandal
Hyderabad 500078, Telangana, India

Tel: +91 40 6630 3997
Fax: +91 40 6630 3998
Web: www.hyderabad.bits-pilani.ac.in

Endorsement from the Head of the Institution of Co-PI

This is to certify that:

1. Institute welcomes participation of Name: **Dr. Kurra Suresh** Designation: Assistant Professor at BITS-Pilani, Hyderabad Campus as the Principal Investigator and **Prof. Srinivasa Prakash Regalla**, Senior Professor at BITS-Pilani, Hyderabad Campus as the Co-Investigator for the project titled "***Development of a low cost 3D DIC system for surface strain analysis in sheet metal forming operations***" and that in the unforeseen event of discontinuance by the Principal Investigator, the Co-Investigator will assume the responsibility of the fruitful completion of the project with the approval of SERB.

2. The Co-PI, **Prof. Srnivasa Prakash Regalla** is a permanent or regular employee of this Institute/University/Organization and has **7** years of regular service left before superannuation.

3. The Co-PI will be governed by the rules and regulations of University/ Institute/Organization/College and will be under administrative control of the University/ Institute/Organization/College for the duration of the project.

4. The grant-in-aid by the SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi will be used to meet the expenditure on the project and for the period for which the project has been sanctioned as mentioned in the sanction order.

5. No administrative or other liability will be attached to SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi at the end of the project.

6. The University/Institute/Organization/College will provide basic infrastructure and other required facilities to the investigator for undertaking the research project.

7. The University/ Institute/Organization/College will take into its books all assets created in the above project and its disposal would be at the discretion of SCIENCE & ENGINEERING RESEARCH BOARD (SERB), New Delhi.

8. The University/ Institute/Organization/College assumes to undertake the financial and other management responsibilities of the project.

Dated: 29.04.2022

Signature of the Head of Institution
Seal of Institution

Deputy Registrar
BITS Pilani, Hyderabad Campus
Jawaharnagar, Kapra Mandal
Medchal District-500 078
Telangana State, India

Undertaking by the Principal Investigator

To

The Secretary
SERB, New Delhi

Sir

I **Kurra Suresh** herby certify that the research proposal titled **Development of a low cost 3D DIC system for surface strain analysis in sheet metal forming operations** submitted for possible funding by SERB, New Delhi is my original idea and has not been copied/taken verbatim from anyone or from any other sources. I further certify that this proposal has been checked for plagiarism through a plagiarism detection tool i.e **Turnitin** approved by the Institute and the contents are original and not copied/taken from any one or many other sources. I am aware of the UGCs Regulations on prevention of Plagiarism i.e. University Grant Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulation, 2018. I also declare that there are no plagiarism charges established or pending against me in the last five years. If the funding agency notices any plagiarism or any other discrepancies in the above proposal of mine, I would abide by whatsoever action taken against me by SERB, as deemed necessary.

K. Suresh

Signature of PI with date

Name / designation

(Kurra Suresh)

Assistant Professor

Certificate from the Investigator

Project Title: Development of a low cost 3D DIC system for surface strain analysis in sheet metal forming operations

It is certified that

1. The same project proposal has not been submitted elsewhere for financial support.
2. We/I undertake that spare time on equipment procured in the project will be made available to other users.
3. We/I agree to submit a certificate from Institutional Biosafety Committee, if the project involves the utilization of genetically engineered organisms. We/I also declare that while conducting experiments, the Biosafety Guidelines of Department of Biotechnology, Department of Health Research, GOI would be followed in toto.
4. We/I agree to submit ethical clearance certificate from the concerned ethical committee, if the project involves field trails/experiments/exchange of specimens, human & animal materials etc.
5. The research work proposed in the scheme/project does not in any way duplicate the work already done or being carried out elsewhere on the subject.
6. We/I agree to abide by the terms and conditions of SERB grant.

K. Suresh

Name and signature of Principal Investigator: Dr. Kurra Suresh

Date: 26-04-2022
Place: BITS Pilani Hyderabad Campus

Name and signature of Co-PI (s) (if any): Prof. Srinivasa Prakash Regalla
Date: 26-04-2022
Place: BITS Pilani Hyderabad Campus